Ricardo Daniel dos Santos Ferreira Nunes

Licenciado em Engenharia Civil

Constructive Characterization of Pombaline Buildings and Simplified Pushover Analysis of Frontal Walls

Dissertação para obtenção do Grau de Mestre em
Engenharia Civil – Estruturas e Geotecnia

Orientador: Prof. Doutor Carlos Manuel Chastre Rodrigues, FCT/UNL

Co-orientador: Doutor Hugo Emanuel Charrinho da Costa Biscaia, FCT/UNL

Júri:

Presidente: Prof.ª Doutora Ildi Cismasiu

Arguente: Prof.º Doutor Fernando Farinha da Silva Pinho

Vogal: Prof.º Doutor Carlos Manuel Chastre Rodrigues

FACULDADE DE
CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

Março, 2017

Constructive Characterization of Pombaline Buildings and Simplified Pushover Analysis of Frontal Walls

To my parents

ACKNOWLEDGMENTS

I would like to endorse my sincere appreciation and gratitude to my thesis supervisor, Professor Carlos Chastre, for his cooperation and uninterrupted dedication along this research, as well as for his passionate participation and great contribution that made possible for me to accomplish this milestone in my academic journey.

In addition, I would like to thank Professor Hugo Biscaia, for his assistance and observations that greatly contributed for the present research.

Additionally, and throughout my academic studies and master thesis, I also would like to acknowledge my deepest recognition to Carlos Simões for his unforeseen friendship, and mostly for his wise and experienced advices.

To my brother, always present to discuss and present new ideas, and mainly for his endless patience.

Finally, but not least, I express my deepest gratitude to my parents, for being so patient throughout this past few years and for all the encouragement, providing me an inexhaustible support, without which this endeavour would never be accomplished.

Thanks for all the encouragement.

RESUMO

A baixa de Lisboa é prova do profundo plano de reforma não só a nível urbanístico como estrutural que Sebastião José de Caravalho e Melo, Marquês de Pombal, instaurou no século XVIII. Houve um cuidado primordial para que a catástrofe que assolou Lisboa a 1 de novembro de 1755 não voltasse a ter o mesmo impacto que teve numa metrópole na altura em plena ascensão na Europa. No entanto, apesar de hoje em dia a necessidade de reabilitar os edifícios Pombalinos ser urgente, o conhecimento estrutural sobre estes está aquém do que seria considerado ideal.

Foi com o objetivo de aprofundar o atual conhecimento destas estruturas que a presente dissertação foi realizada. Inicialmente apresenta-se a contextualização histórica de como era a cidade de Lisboa sucedendo-se o estudo acerca do sismo de 1755 e das suas consequências. Posteriormente, foi dado enfoque ao período pós-sismo, mais concretamente nas ações levadas a cabo pelo Marquês de Pombal com a sua equipa de engenheiros. Aqui, para além das ações imediatas para reestabelecer a ordem, foi dada importância às medidas construtivas que por ordem de Marquês de Pombal foram aplicadas na construção dos novos edifícios.

Foi então descrito o típico edifício pombalino desde as fundações até à cobertura dando-se uma especial atenção à gaiola pombalina e às suas ligações, introduzindo-se à posterior a análise estrutural da gaiola pombalina. Deste modo, e sendo o edifício pombalino um conjunto de várias estruturas interligadas, considerou-se a parede frontal a peça-chave estrutural, procedendo-se assim a uma análise mais detalhada da mesma.

Por último e após a modelação de ensaios experimentais representativos dos frontais existentes nos edifícios pombalinos foi apresentada uma metodologia de análise deste tipo de estruturas. Com esta metodologia, tornar-se assim mais expedita a obtenção da curva característica aproximada do comportamento dos frontais quando sujeitos a forças horizontais, o que facilitará a análise sísmica dos edifícios Pombalinos.

PALAVRAS-CHAVE:

Edifício pombalino, paredes frontais, análise sísmica.

ABSTRACT

Lisbon's downtown is the proof of the profound rehabilitation effort done by Sebastião José Carvalho e Melo, Marquês de Pombal, in the 18th century. The main objective was to prepare Lisbon for another event like the 1st November, 1755, preventing a massive destruction from happening again in a up growth European city. However, and despite the imperious demand to rehabilitate these downtown historical buildings, the level of structural knowledge is not yet considerably solid.

It was with the purpose of expanding the structural behaviour knowledge in these structures, that the present research was based. It started with a historical overview of Lisbon before 1755 earthquake followed by a brief description of the tragedy and its consequences. Coupled with, was the description of the actions taken by *Marquês de Pombal* and his engineer's team. Here, not only the laws to re-establish the order were described but also the major measures implemented in the building's reconstruction process.

The description of the typical Pombaline building from its foundation to the roof followed the initial part, with special attention to the *gaiola pombalina* and its connections, introducing therefore the ensuing structural analysis of a common *frontal wall*. Considering a typical Pombaline building as an interconnection of numerous structural individual members, it was considered that the most relevant one is the wall, thus proceeding for a wall structural model.

At last and following the previous analysis, it was presented a methodology for a fast obtaining process of the structural behaviour of this type of walls. Thus, obtaining the response of these walls when submitted to horizontal forces is far more prompt, simplifying in the future the seismic analysis of an entire Pombaline building.

KEY-WORDS:

Pombaline building, frontal walls, seismic analysis.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL CONSIDERATIONS

Lisbon, one of the biggest European cities in the18th century, suffered a major catastrophe on the 1st November 1755, a devastating earthquake, followed by a large tsunami and an enormous fire (Chester, 2001). Despite the city devastation, this impelled Lisbon authorities to review the actual urban plan, which was in fact inexistent (Mascarenhas, 2004). The main objective was to reinstall the feeling of security in the population and prepare the city for a new era and economic development.

The reconstruction was outstanding and represents nowadays a landmark in the Portuguese history. This demanding and rigorous task involved some of the greatest well known individuals, not only in architecture, but also in civil and urban planning engineers. Changes ranged from the sewer system to the symmetric façades. At the same time, the legislative part was undoubtedly a major aspect, and worthy to be mentioned, allowing the re-establishment of the security, on the one hand, and, on the other, forced the execution of the urban plans. All these measures enabled the reconstruction of the city and brought the calm and order to Lisbon.

The buildings built during the reconstruction period after the earthquake are known as Pombaline buildings and one of the most relevant peculiarities of this buildings is the Gaiola Pombalina, a tridimensional timber structure filled with weak masonry and designed to provide seismic resistance to the buildings (R. Cardoso, et al., 2005).

Despite the inexistence of an official document forcing the implementation of these structures, all Lisbon downtown buildings have the *Gaiola Pombalina*, its main principle being the reduction of the building weight and the increase of its flexibility, which are needed in a seismic event. Fortunately, although there has not been such a huge earthquake to test the *Gaiola Pombalina* structure in a real scenario, recent studies (Goncalves, et al., 2015; L. Kouris, et al., 2014;

Pompeu Santos, 1997) with real wall samples have showed that for such an ancient structure the resistance is extraordinary.

Despite this extraordinary achievement, Lisbon is undergoing a new rehabilitation era, where the demolition of the *Gaiola Pombalina* timber structure is a constant. The fact that the Pombaline buildings are not considered world heritage by UNESCO, combined with the scarce knowledge in their rehabilitation, leads to the demolition of the Pombaline buildings’ central core.

1.2 MAIN OBJECTIVES

Recent studies (Ferreira, et al., 2012; Goncalves, et al., 2015; Meireles, 2012) have been developed about the reconstruction of these approximate three-century-old buildings. With this intention, i.e. to deepen the current knowledge in this type of construction and the construction techniques, the present work has as a main goal to simplify the seismic structural analysis of a typical Pombaline building.

Therefore, as a starting point, it is important to understand the catastrophe that was the driving force for the seismic construction under analysis and the change of the Lisbon city layout. The plans, the laws and the actions taken after the earthquake will be described.

This introductory part is crucial for a correct perception and awareness right from the origin to its present state, including the modifications occurred along the time. Also, it is the objective of this initial part to investigate the Pombaline construction as a visionary and innovative idea for a structural code that obliges constructors to give a so called, “safety guarantee” to its inhabitants.

After that, and still related to the first part, the objective is to describe some of the construction techniques used to interconnect all the elements that all assembled constitute the ‘*gaiola pombalina*’. This awareness of how the structure is assembled and the mechanics involved, will be decisive for a better understanding of the results of the seismic analysis.

Given these points, and after the preliminary knowledge acquired, the main goal will be to study the Pombaline walls individually (also called ‘*frontal* walls’). The walls will be submitted to a pushover analysis in order to understand their ultimate mechanical resistance to shear forces. Consequently, this achievement will be primordial for the development of simpler models.

1.3 THESIS LAYOUT AND ORGANIZATION

Considering the objectives previously described, the current thesis is organized and divided in seven chapters, including the introduction and conclusion, which are briefly described:

The **chapter 1,** introduces the present research establishing the main objectives and guidelines.

In **chapter 2** a description of Lisbon city is presented. This part is important to understand the evolution of the city during the three centuries prior to the earthquake and the reasons that triggered the erratic construction all over the Lisbon region. In addition, there is a description of the tragic earthquake, which was followed by a tsunami and a fire. It is a description based not only in scientific facts but also in preserved memories from real people who lived this tragic event.

Chapter 3 is dedicated to the description of the main ideas developed to rebuild Lisbon, which were included in *Manoel da Maia* thesis. Furthermore, the well-known *Marquês de Pombal* innovative actions that were crucial to re-establish the calm and rebuild Lisbon are also presented. Besides that, the pioneering civil protecting measures implemented in the buildings in order to prevent another catastrophe in the city are explained.

Chapter 4 describes the evolution of anti-seismic construction techniques and their associated legislation, with the intention of establishing a connection between the laws implemented by *Marquês de Pombal* and the current construction codes. In addition, other anti-seismic solutions are compared and analysed.

Chapter 5 presents a concise description of the Pombaline building. The main objective is to understand how the new city buildings were erected right from their foundations up to the roof. Included is the description of the most common interconnection between elements, and the techniques used to do it. It is also important to mention that along with the research work necessary to successfully produce this chapter, a field research complemented all.

In **chapter 6**, and based on the previous knowledge acquired, the *frontal* walls were analysed. The objective was to study their response when submitted to lateral forces and perceive how their behaviour could be predicted. Structural models using the software SAP 2000(“SAP 2000 - Integrated Software for Structural Analysis & Design,” 1998) were performed coupled with a proposed model and a methodology to simplify the seismic analysis of this type of walls.

Finally, the **chapter 7** resumes all the conclusions reached throughout all the research done. Some suggestions are also proposed in this section, leading the way for future work related to this subject.

CHAPTER 2

LISBON HISTORICAL OVERVIEW

2.1 GENERAL OUTLINE OF LISBON - 15TH TO 18TH CENTURIES

The strategical geographic position of Lisbon - as it is known nowadays - nearby the Tagus River estuary was the primordial key reason for the fast development of the city in its early times. Fertile soils, the estuary offering perfect conditions for a port[1] and the naturally protected plain terrain between two major hills - known today as *S. Francisco´s* and *Castelo´s* hills - are some of the reasons that attracted people to move to this region. Therefore, the fast-growing population brought with it the need of building more and more houses, as well as the necessity to create all the infrastructures required in a city. Thus, and as the city rapidly increased, a typical Muslim (Mascarenhas, 2004; V. Oliveira and Pinho, 2010) city (heritage left by the occupation of Muslim forces during the Middle Ages and Renaissance) was being raised in a chaotic and poorly organized environment (Figure 2.1). The buildings were constructed in the insecurity of alluvial soils additionally to a complete disregard or any attention for circulation, sanitation and safety against natural phenomena (like earthquakes) or others. To sum up, Lisbon was not being founded with a proper urban plan, as well as it was not offering protection to all of its residents. The constructed buildings, until 1755, had many flaws, mostly of them structural, that represented an imminent risk for the population in case of catastrophe. Several examples could be pointed out to better realize this previous statement. First of all, the balconies protruding the facade with poorly connections to the structure as well as the chimneys in the roof tops, signify a great risk in case of an earthquake. This “secondary” structures will detach from the main structure and fall apart in the streets striking any person escaping. Secondly, the arches very common at the

---

[1] Lisbon’s port was one of the major ones in Europe. Influenced by the Portuguese age of discoveries, at the time, this important infrastructure played a critical role in the development of Lisbon. Not only improving commercial trade between countries, but also contributed to the increase of city population that rapidly develop from 50,000 – 60,000 inhabitants to 100,000 at middles ages of 16th century. At 1620 a population of 165,000 makes Lisbon the largest city in Europe, after Seville with 120,000. In 1755, reports state a record of 200,000 inhabitants (Barreiros, 2008).

buildings ground floor, with the purpose of inter connecting streets and creating easier passages between them, represent a great risk in case of collapse. If that would happen, exits would be blocked and ways to reach a safer zone would be harder to found. Other example was the construction of buildings on top of arcades. This solution was intended to give a wider and spacious area for the improvement of all commercial trades. However, if it was a good solution for the trade, it was not the best solution for this kind of buildings, considering that an open space at the ground floor would collapse more easily than a standard floor with walls.

Figure 2.1 – Lisbon street layout previous to the 1755 earthquake. *“Olissippo quae nunc Lisboa, civitas amplíssima lusitaniae, ad tagum, totius orientis, et multarum insularum africaeque et americae emporium nobilissimum*". Portugal, Tombo’s Tower, Castilho’s Colecction. Pt18, doc 165.

Similarly, the unequal height of adjacent buildings was also a serious problem if an earthquake occurred. Additionally, and to make matters worse, the use of unprotected timber[2] represented a key-factor to an easy fire propagation throughout the city, a catastrophe that should be prevented at any cost.

Furthermore, the flooded soils where the city was being constructed, represented a major threat to all citizens. The flat and low altitude of Lisbon’s downtown terrains (taking the level of sea

---

[2] The use of timber for structural proposes directly exposed to the elements.

waters as a reference) facilitate the sea entrance in the city and possibly, its destruction in case of a tsunami occurrence.

Finally, the sanitation issues were a huge problem for the city as a primary reason for diseases and plagues. The lack of a sewage system forced people, at the time, to dump all the waste in the public street, penetrating the flooded soils and consequently polluting them. As matter of fact, this not only pollutes the soils as well as reduces drastically the soil bearing capacity (increasing liquefaction problems), leading to a major impact in all the infrastructures placed above (Mascarenhas, 2004).

To sum up, several weaknesses could be pointed out to the Lisbon layout and their constructions before the year of 1755. Although the lack of a proper urban plan was the most important one. This one would make possible to a fast growing city the development in an appropriate and well-organized way, knowing in advance what kind of problems would exist in the future, and what could be prevented to happen.

2.2 THE 1755 LISBON'S EARTHQUAKE

In 1755, November 1st at 9:40 a.m., an earthquake struck Portugal with a magnitude of 9 (C. S. Oliveira, 2008). Shock waves were felt throughout Europe and northern Africa, with major consequences in Lisbon and Algarve.

It was 'All Saint's day' and the people were attending the divine worship throughout all the churches in Lisbon. According to the tradition, all of them were lighted up with candles that contributed to a fire with greater consequences than the earthquake itself.

The immediate deaths were shockingly tremendous, mostly by virtue of the collapsed churches. 30 out of the 40 churches in Lisbon felt down killing the faithful people immediately (Mendes-Victor, et al., 2009). Several memories and theories were written about the earthquake impacts. Philosophers like *Immanuel Kant*, or the knight of the royal house and Christ Order *Jacome Ratton* wrote theirs. *Ratton* states: "(…) I went to the *Carmo's* church afterwards, and the stone vault ceiling fell down, killing many people that stood beneath it (…)" (Ratton, 1813) (p.24). After the earthquake, more precisely, 30 minutes after (Mendes-Victor, et al., 2009) (p.44), a *tsunami* (with 6-meters high waves (Chester, 2001) engulfed Lisbon downtown. Several people who were escaping from the collapsed buildings took refuge in *Terreiro do Paço* square but were instantly drowned, increasing even more the tragedy numbers. Many other people tried to escape the city by boat and were hit by these huge waves that easily sank their vessels. Those who could run away took protection in higher grounds. *Ratton* wrote in his memories: "Soon afterwards we arrived there, as many other people, someone started to shout that the sea was furiously coming up (…) increasing our terror (…)"(Ratton, 1813) (p.25).

Shortly after the earthquake the city started to burn down (Figure 2.2). The collapsed buildings were the fuel to this fire, which remained active for 6 days and the smoke produced by it could be observed from *Santarém*. This one was even more destructive than the earthquake itself, destroying what was left over. Also, wind gusts blew for days after the earthquake and outlaws that had evaded, promoted the fire propagation throughout the city (Mascarenhas, 2004).

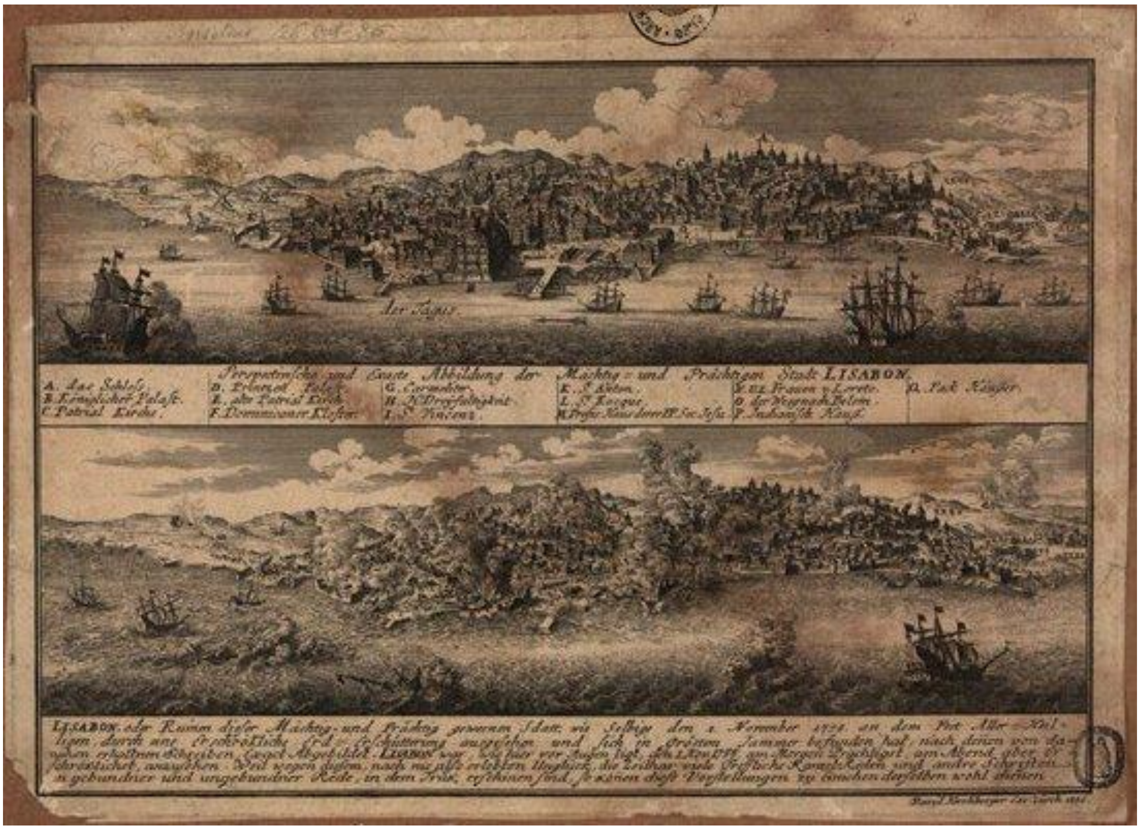


Figure 2.2 – Lisbon before and after the 1755 earthquake – "*Perspectiva e exacta panorâmica da poderosa e explêndida cidade de Lisboa" and "Lisboa ou ruínas dessa poderosa e explêndida cidade a 1 de Novembro de 1755".* Portugal Tombo's tower. Castilho's collection, pt.17, doc 75.

The earthquake had its epicentre about 200 km west-southwest of Cape St. Vicent in the Atlantic ocean (Aguirre, 2012) and had various stages. The first vibration, as previously said, was felt at 9:40am and lasted for about 90 seconds, being followed by a break of approximately 1 minute. After that, a second shake, considerably stronger than the first one, with a duration of 2 minutes and 30 seconds occurred. Afterwards, there was a pause of 1 minute, and a third shake stroke the city again, this time for approximately 3 minutes. Lastly and after a much longer interruption of 1 hour and 11 minutes, a fourth shake. This time just for a few seconds (Mascarenhas, 2004). In the 24 hours that followed, replicas of the original earthquake were felt, even though with less significance than the first one, but that was enough to maintain the fear among the survivors.

There is no accurate record of how many deaths could be related to those catastrophic events. Differing from source to source, there are numbers from 6,000 up to 100,000 (Aguirre, 2012). However, an estimation of 10,000 deaths can be directly related to the earthquake (Chester, 2001).

Surely all buildings in Lisbon suffered major damage, almost the entire city was torn down. Only 10 out of the 75 convents[3] stood still. The Arsenal, 33 palaces, the Patriarchal palace and the Royal Library were destroyed (Chester, 2001). An urgent plan had to be made to turn Lisbon to its greatness and to re-establish the order and the normality in daily life.

---

[3] Not including the 30, out of 40 churches, that collapsed.

CHAPTER 3

LISBON REBUILDING ACTIONS AND PLANS

3.1 *MARQUÊS DE POMBAL* AND *MANUEL DA MAIA*

Born on 13th May 1699, *Sebastião José de Carvalho e Melo*, also known as *Marquês de Pombal* (Figure 3.1) was a Portuguese noble and diplomat that played a major role in Portugal's history during the 18th century. His experience in Europe, mainly as the Ambassador of Portugal in London (1739 to 1742), gave him a different perspective when he returned to Portugal in 1749, where such a liberal and cultural society environment did not exist. Right from the beginning, his will to apply in Portugal an European culture and policy was definitely a landmark of all his work reforming the country in social, economic and administrative ways.

Figure 3.1 – *Marquês de Pombal* portrait (National Portugal Library - cod. E-2051V)

Nominated in 1750 minister for the internal affairs of the kingdom by the King D. José I (1714 - 1777), he occupied that position for 27 years. He his highly praised for his prompt reaction to Lisbon's 1755 earthquake and all the measures he took to properly rebuild the city.

In charge of restoring Lisbon to its glory, reconstructing it in a brilliant and never seen approach, *Marquês de Pombal*, founded the office known as *Casa do Risco e das Obras Públicas do Reino*, responsible for the projects design. In charge of that office a group of architects and engineers designed all the city new plans, along with the construction techinques to be applied in the construction. That important renovation process had brilliant minds behind it, that were the moving force to *Pombal*'s ideas. Although, one man could be referred as the mentor of this project: *Manuel da Maia*[4].

Maia, being at the time 80 years old, was the chief-engineer of the kingdom and responsible for numerous constructions ordered by the king, namely the ambitious project for water supply Lisbon: *aqueduto das águas livres*. Also important to mention was his role as the main keeper of the national *Tombo's* tower, where he was responsible for preserving all the historic documents of the utmost importance related to Portugal's history. Thus, *Marquês de Pombal*, aware of his knowledge and vast experience, designated him to produce a document where a first approach to Lisbon reconstruction was presented. That document became known as *Manuel da Maia* dissertation and had three parts, each one giving continuity to the work described in the previous one.

Even though *Maia* was the greatest "driving force" of this renovation process, the work done by other important engineers, who he worked with, could not be obliterated. By chronological order those were: *Eugénio dos Santos e Carvalho*[5], *Carlos Mardel, Reinaldo Manoel de Sousa* and *Manoel Caetano*.

3.2 IMMEDIATE ACTIONS AFTER THE EARTHQUAKE

Soon after the earthquake, and before any construction was made, the city needed to re-establish its feeling of security and ensure that its inhabitants would not desert it. Likewise, important measures had to be taken to guarantee that no insecure construction was done before the plans and projects for the new city were concluded. Hence, during that period, *Marquês de* Pombal enforced a set of laws with immediate action in Lisbon that became known as *providências*. The most important ones will be here mentioned.

First of all, and aiming to protect all Lisbon's tragedy survivors, a role of laws was set in order to restore the calmness and prevent further problems to the ruined city.

Immediately afterwards the earthquake and consequent catastrophes, Lisbon city was invaded by gangs of thieves and murderers that had been exacerbating the violence, looting and, to make

---

[4] Also written Manoel da Maya.

[5] Also written Eugénio dos Santos de Carvalho.

matters worse, setting more fires throughout Lisbon. Therefore, and to prevent this crimes of happening so frequently, at November 4th 1755, merely 4 days after the earthquake, a law was decreed making possible immediate verbal trials in the streets for whoever was caught perpetrating any public violence or disorder. This prevented the usual and common slow process of judging someone for their crimes, and consequently, gradually, the process to restore the city normality begun.

Another important measure taken by *Marquês de Pombal*, was to prevent a plague in the city of Lisbon. Many corpses were decomposing in the streets, creating the perfect conditions for a plague proliferation. With this in mind, all bodies were thrown in the sea without any funeral celebration or religious ritual, making as the primary objective to “bury the dead and take care of the living ones”.

Other urgent and immediate actions can be presented (FLAD, 2005):

- Prevent the population from dessert the city. Exiting the city was at the time only allowed with a special authorization;
- Send military forces to Lisbon, not only to help in the city works, but also to contribute in restoring the normality to the streets;
- Give the proper conditions to the citizens to live until all the reconstruction was finished;
- Prevent people for starvation and heal the wounded.

Secondly, immediate laws to avoid a rapid construction proliferation of insecure houses throughout the city was crucial, before any reconstruction plans were made. This actions had the main objective of ensuring that the city would rise again, but this time considering the errors made before, avoiding them. *Pombal*’s intention was to create a landmark in Portugal’s history, and worldwide, avoiding the amount of deaths that an earthquake, fire, or other natural disaster can inflict in a densely populated city.

Amongst all the actions taken regarding the construction process, the ones presented below, were undoubtedly the most relevant ones in this renovation process (FLAD, 2005).

- Measures to restrain the price speculation of construction materials were essential. Therefore, at November 10th 1755, a law pretending to control this market was enforced;
- For a better assessment of the tragedy material losses, it was made a data collection and assessment of all the properties and streets. This was imposed by the law of November 29th 1755. It was very important to later grant that the landlords would not lose any property in the new project plan, and also, if that was the case, be compensated for any expropriation that could occur;
- Prohibition to erect new buildings came into action with the law of December 3rd 1755. That legislative document also “froze” the house rents and delimitated the area of Lisbon were these construction laws were imposed.

Later, with the city new plans made in 1758, two important law documents cannot be neglected. Those were the law of May 12th 1758 and June 12th 1758. They, as it will be analysed later in this document, represented the turning point for Lisbon and the reconstruction start.

In addition to all the laws presented, another crucial and unprecedented action after a natural disaster was taken: a survey inquiring about the earthquake damages and consequences (Mendes-Victor, et al., 2009) (p.51). This crucial information, still used today by many researchers, represented a huge contribute for the following generations, being regarded as the cornerstone in the study of earthquakes.

To sum up, it can be said that all the legislative conditions were created to ensure that the city reconstruction could begin in a sustainable way.

3.3 CONCEPT PLANNING: POTENTIAL WAYS FOR LISBON'S RECONSTRUCTION

At the same time this crisis actions were being taken, *Marquês de Pombal* designated *Manuel da Maia* to present several plans for Lisbon reconstruction. *Manuel da Maia,* a man known by his practical knowledge and aware of the need to re-raise the city with improved security and sanitary conditions, has delineated 5 possible plans, and for each one the corresponding benefits and weaknesses. Other engineers and architects not mentioned in records certainly played an important role too, planning and analysing every option carefully.

Manuel da Maia's commitment to improve Lisbon's older urban plan, as it was made in London and Turin before (*Maia*'s dissertation, part II - §3, 11 and part III - §14, 15) when they were also struck by huge catastrophes, cannot be questioned. Numerous were the design ideas for Lisbon that he wrote in his dissertation with the purpose of presenting and explaining each one to the King. Thus, the dissertation with the title "Dissertation about Lisbon city renovation" [6], is a document divided in 3 chained parts. A fourth part was intended to be written by the author, but unfortunately that did not happen, with no explanation found until today.

The first part could be considered as a first analysis and an introductory chapter to potential ways for Lisbon's reconstruction. Thus, at December 4th of 1755, roughly one month after the earthquake, *Manuel da Maia* finished this part and presented it to the King. In it were 5 rebuilding ideas for Lisbon, amongst other important notes.

The first idea (or *"modo"* as the author named it), consisted in rebuilding the entire city as it was before the earthquake (*Maia*'s dissertation, part I - §2). Hoping that in a near future a new earthquake would not happen, and with the desperate need to reallocate the inhabitants, this sounded like a possible and plausible plan. Although, this would not solve the inherent structural

---

[6] A copy, handwritten by *João Batista de Castro (*or *Joam Bautista de Castro)*, is still preserved today in *Évora*'s public library. There, the first two parts and the beginning of the third one up to the 6th point (Codex CXII/2-9) can be requested for reading. The third part is in the Military archive at *Tombo*'s tower.

problems that the precious constructions presented and neither would provide the feeling of security the people so desperately needed.

The second one (*Maia*'s dissertation, part I - §3), bore a close resemblance to the first one, with a slightly difference: the existing narrow streets would be larger and the buildings would not be higher than they were before. This solution, similar to the previous one, did not present significant changes benefiting the population.

The third plan (*Maia*'s dissertation, part I - §4) was an evolution from the last two previously presented. The widening of the streets was maintained but, this time, a three-story building limitation would be imposed to new constructions. This solution would give a well-organized aspect to the city, despite the loss of property imposed to some landlords. The response due to a fire or earthquake would also be improved with this solution.

The most important one, and fourth plan (*Maia*'s dissertation, part I - §6), subsisted in a radical solution: tearing down all the buildings and, on top of the ruins, erect the new city. This plan proposal suggests a total new layout of the streets where the height of the buildings would depend upon the streets width. Thus, if a building collapses, that would not affect the close ones, preventing a chain reaction. Other advantage was the construction on top of the ruins that contributes for rising the terrain above the level of sea water and extending the land inwards the river. This would also provide perfect draining conditions against the usual floods. However, a major weakness to this plan, due to the new streets layout, was to compensate or give the fair part to each one of the land lords.

At last, the fifth plan (*Maia*'s dissertation, part I - §7). This one proposed to start a new city between *Belém* and *Pedrouços* or in *Belém*. The old one would be abandoned and a new city well-planned right from the beginning would born. The main advantage comparing with the other plans were that the city could be constructed in a faster pace than rebuild the old (and destroyed) one. At first glance this appears to be a good solution although some obstacles could be found, especially the loss of property that would be implied to the land lords, and the relocation of all infrastructures to this new site.

The King, after analysing all the 'pros and cons' implied to each project plan (clearly explained in *Maia*'s part I dissertation), chose the forth one as the best solution for Lisbon. Therefore, in some way pleased with the recognition given by the King to his ideas, *Manuel da Maia*, continued his work and wrote the second part, finishing it at February 16th 1756. In this one, and benefitting from the data collected mentioning the problematic streets, he presented three possibilities for the reconstruction regarding the forth plan selected. The first idea (*Maia's* dissertation – Part II - §3) is equal to the forth one previously mentioned in *Maia*'s dissertation part I, but this time he presented some solutions regarding the practical applicability. In other words, tearing down all the buildings and increase the width of the streets carries out the problem of reimbursing the landlords for the loss of property. Therefore *Maia* suggested that all the buildings and respective lands should be evaluated accordingly to a fixed price per area before tearing down their properties. Thus, after the demolition every landlord should receive or pay their share, accordingly if their property was decreased or increased by virtue of the new streets layout (*Maia's* dissertation – Part II - §3, 5).

The second and third idea (*Maia'*s dissertation – Part II - §4) share the same intention of maintaining the pre-earthquake street layout. However, while in the second one only the narrow streets would be widened and the alleys would be kept blocked, in the third option the streets would be widened too but all the alleys would be opened preventing the blockage of certain areas. It is perfectly noticeable at this point that, *Manuel da Maia,* is applying his knowledge and experience to avoid the same errors to occur, especially the ones that stopped people from escaping safely to a safer zone when the catastrophe occurred.

Hereupon, and after *Maia's* ideas were presented he stated that the first option was the most suitable one (*Maia*'s dissertation – Part II - §6). His predominant reason was that the project would be easier to concretize comparting to the other ones presented.

In this part, another point worth mentioning is that a period of time was given to each landlord to start and finish all the works, taking as reference for the reconstruction all the drawings that would be given by the Captain *Eugénio dos Santos e Carvalho*, senate architect. The main objective was to give the same architectural aspect to all the buildings, so that the symmetry of windows, doors and other characteristics of the buildings would be respected (*Maia*'s dissertation – Part II - §6). Furthermore, in this paragraph *Manuel da Maia* mentioned the importance of building fireguard walls between properties, which would be higher than the rooftops, preventing the fire propagation from building to building. Again, this special details are of great significance, preventing errors made in the past to happen again.

At last, and after the King analysis of the *Maia's* second part dissertation, he preferred the first alternative, allowing *Manuel da Maia* to continue his work and write the third part.

3.4 GUIDELINES FOR THE RECONSTRUCTION: STREET LAYOUT PLAN

The third part of *Maia's* dissertation concluded on 31st March 1756, presented the final guidelines to the reconstruction. In this part, *Maia,* acknowledging right from the start that his capabilities to execute the blueprints and drawings were considerably affected by his advanced age*,* he designated the architect teams responsible for those works (*Maia's* dissertation – part III - § 1, 2, 3) and also suggested the group of engineers[7] responsible for the coordination of the construction – the plan that would be chosen by his highness *D. José I* (*Maia's* dissertation – part III - § 11). It is also important to mention that all the engineers and architects nominated to this project were official members of the Military Academy.

---

[7] The engineers chosen by *Manuel da* Maia, were Lieutenant Colonel *Carlos Mardel* and the Captain *Eugénio dos Santos de Carvalho.* Later those ones were replaced by Reinaldo Manoel de Sousa and Manoel Caetano.

Therefore, three architect teams were proposed by *Maia* to develop the blueprints for the new possible city layout. Each team produced one, corresponding to the layouts number 1, 2 and 3 presented in *Maia's* dissertation (*Maia's* dissertation – Part III - §1,2,3). By the same order the layouts were numbered the teams who designed them were formed by *Pedro Gualter Fonseca* and the practitioner *Francisco Pinheiro da Cunha,* Captain *Elias Sebastião Pope* and his son practitioner *Jose Domingos Pope* and finally Captain *Eugénio dos Santos de Carvalho* and his assistant *Antonio Carlos Andreas*.

Additionally, another 3 blueprints were drawn, corresponding to the numbers 4, 5 and 6, respectively produced by *Pedro Gualtar da Fonseca*, *Eugénio dos Santos e Carvalho* and *Elias Sebastião Pope.*

The one chosen was the fifth one and to that one *Manuel da Maia* made no special demand, which lead to a total design freedom (even regarding the position of churches, temples and chapels) for *Eugénio dos Santos e Carvalho*. It is also important to mention that in the 5th plant (Figure 3.2) the yellow colours represented what would be new, and the red what would be conserved in its original place.

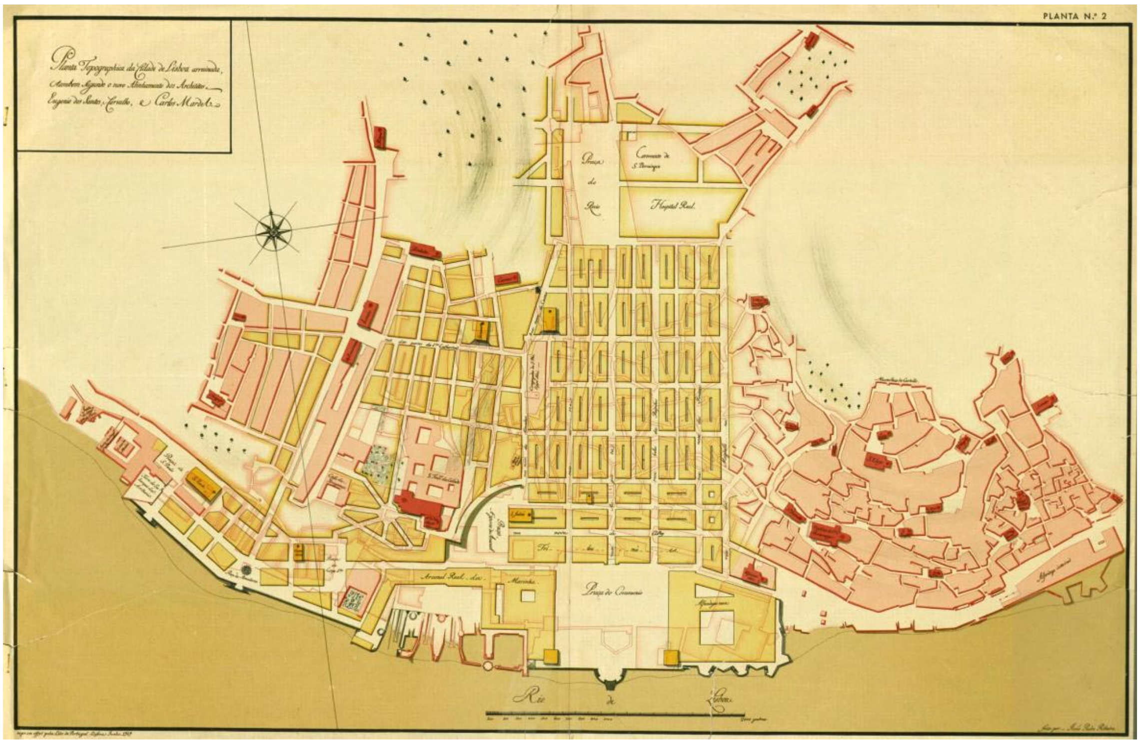


Figure 3.2 - Ruined Lisbon city topographic plant, according to the new alignment by the architects *Eugénio dos Santos e Carvalho* and *Carlos Mardel*. Lisbon's city Municipal Archive. (Cod: PT/AMLSB/CMLSB/UROB-PU/11/456/02)

Besides the layout for the streets, in this third part five drawings are also presented. These ones focused mainly on the architectural details of the buildings, namely a cut section of the streets can be contemplated where the typical three zones division (likewise it was made in England) is represented as well as the new sewage system that would be implemented (see Figure 3.3). In the other 4 drawings, references to the symmetric of buildings, heights and fireguard walls are present along with a possible architectural solution for *Terreiro's do Paço* buildings (*Maia's* dissertation – Part III - §15,16,17,18,19).

3.5 CONSTRUCTION FEATURES REGARDING CIVIL PROTECTION

After the project plan was authorized and approved, the works begun at May 15th of 1756 (Mascarenhas, 2004). Several noteworthy features could be pointed out at this stage to the layout chosen as well as to some relevant aspects regarding architectural features that contributed for the population's safety in case of another natural hazard would occur.

First of all, and from the observations done to the collapsed buildings at the time, it was possible to conclude that the earthquake presented a North-South shock orientation[8]. Thus, and according to that fact, all the principal streets and respective blocks were aligned in that direction, as can be perceived in Figure 3.2. This perfect alignment, not only contributed to give a better response to buildings in case of an earthquake, but also had the purpose to better guide the population towards the large squares, where they could be away from falling buildings. The open street layout with no alleys, in addition to large streets represented a major improvement to the security of the population. Also, the natural streets ventilation was enhanced with this solution.

Secondly, the architectural symmetric façades law that all the landlords were obliged to apply during the construction of their buildings, gave an equal and "clean" look along the streets. This also brought some major enhancements, namely, a greater structural response to earthquakes as well as the secondary structures protruding the façade ceased to exist.

Also regarding the streets, *Manuel da Maia* presented an example of a street cut section similar to the ones applied in London at the time, i.e. the streets would have 40 spans[9] for chariots (or other type of vehicles) and 10 spans in both sides for pedestrians, separated from each other, corresponding to a total width of 60 spans (*Maia's* dissertation – Part III - §14, 15). Other notable aspect worth mentioning is the landfill next to the Tagus River made out of the old city ruins. This solution raised up the ground level for construction preventing the usual floods originated by ocean's tide or simple natural floods. The depot's slope also contributed to a better draining all over the reconstruction area towards the sea (*Maia's* dissertation – Part I - §6). Another major feature idealized by *Manuel da Maia* was the sewage system that would be constructed connecting all the major streets underground in Lisbon. Its fundamental objective was to get rid of all waste and pluvial waters channelling and dumping them to the river, thereby cleaning all the streets. *Manuel da Maia*, also refers that *Sacavém* River could be the proper place to do so. The system's basic principles of working were basics. All the buildings had an inside courtyard -

---

[8] According to recent studies the earthquake had a predominant NNW-SSE orientation, proving that the assumptions made at the time were not so far from the reality (Mendes-Victor, et al., 2009).

[9] Span is a distance measure from the thumb to the little finger, corresponding to a distance of 22,5cm.

Alfurge[10]- that was connected by an underground duct to the main sewage duct – *cloaca*[11]. This last one had the capacity to receive all the waters of all the buildings that were connected to it. Thus, every inhabitant living in buildings provided with an '*Alfurge'* (see Figure 3.3) simply had to open the window that leads to the inside courtyard and dump their waste. Also, pluvial waters were channelled to this courtyard too. All the streets that were not provided with the main sewage duct, every morning a carriage would collect the garbage and solid waste, cleaning as well those streets too (*Maia's* dissertation – Part III - §5, 6, 7, 8). It is also important to refer that this system contributed not only to reduce drastically the so common diseases, mostly plagues, but also prevented the soils from soaking in water reducing consequently the risk of liquefaction.

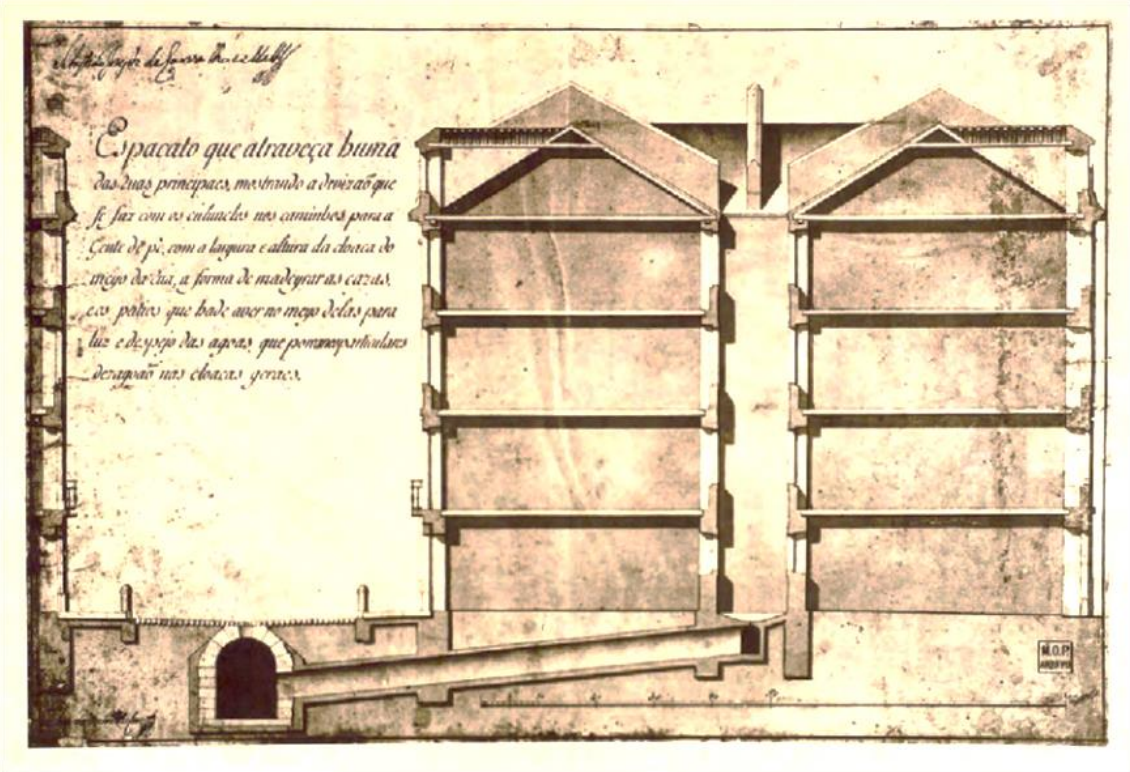


Figure 3.3 - Cut view of a Pombaline building, sewage and streets. *Eugénio dos Santos e Carvalho*, 1758. Historical archive of the public works department.

Lastly, the problems that arise from the fire propagation were not obliterated and were covered too in this city renovation. *Manuel da Maia* aware of the destruction that the fire after the 1755 earthquake inflicted on buildings and their inhabitants, tried to prevent that of happening again. Thus, he suggested in his dissertation that water pumps must be spread throughout Lisbon downtown in order to fire fight efficiently. Also, and coupled to all the pumps would be a good set of leather buckets.

---

[10] Inside courtyard that exists in the middle of the house blocks for the purpose of light the houses naturally, and for the disposal of waste water as well as pluvial ones too. It had 5 to 6 spans width, and none of the buildings had doors to access it, only windows (*Maia's* dissertation – Part III - §7).

[11] Main sewage duct that goes underground in the major streets. It had 10 spans width and 14 spans height –12th June 1758 law - §15.

Even more, *Maia* also suggested that every street had a fountain or every house had a water tap, similar to a fire hydrant we have nowadays. But, not only "active fire fight systems" were mentioned in his dissertation, but also a passive and very important one is highlighted quite often throughout the text: firebreak wall. This wall, with no openings, would be constructed separating buildings from each other and would be higher than the building itself preventing the fire propagation even between rooftops. However, this fire system implied the (so needed and requested by the population) improvement of the water supply to the city. Thus, and to overcome this prompt necessity of water, and also to better cover the population's needs, Maia suggested the '*Águas Livres'* aqueduct improvement. With this upgrading it would also be possible to supply the major square's fountains (*Maia's* dissertation – Part III – §9).

3.6 LEGISLATIVE ASPECTS AND THE FAÇADE ARCHITECTURE

The city's renovation ambitioned to decrease the number of deaths in case of a future earthquake strikes the city, preventing the 1755 catastrophe to happen again. The rectilinear layout previously described, along with large streets directly connecting to the major squares, represented a considerable improvement but, if the buildings collapse immediately, the purpose of having those "escape routes" would become useless. So, above all, a new design and concept for the buildings making them able to withstand such forces was a must and a safety priority.

Aware of the complexity inherent to this important project and intending to give a new look to the downtown of Lisbon, *Marquês de Pombal* founded the *Casa do Risco*[12] after the earthquake to study and produce all the projects needed for the city reconstruction. Thus, *Casa do Risco*, respecting and taking as a guideline all the dissertations written by *Manuel da Maia*, produced the *Cartulário Pombalino*[13], a set of drawings regarding the unique façade architecture that all the landlords must respect during the construction of their buildings. Although, it is important to mention that all these new drawings do not respect the original *Maia*'s idea of a two-story buildings.

After the project approval, the urbanistic laws started to be created in order to begin the so waited city reconstruction. Despite the number of laws that were published during those time, two of them surely cannot be neglected, since they are certainly the most relevant ones which impelled this rebuilding process: the decrees of 12th May 1758 and 12th June 1758. The first one essentially outsets the all process of reconstruction explaining how the properties would be "redistributed" throughout all the landlords and how the monetary compensation process would be done. Furthermore, a deadline of 5 years was imposed to all constructions after the legal authorization was provided, thus preventing the excessive extension of time construction. One month after, at 12th June 1758, the most important decree was released. This one could be known as the plan to

---

[12] Also known as *Casa do Risco das obras públicas do reino.*

[13] A set of 70 drawings called *prospectos* (in Portuguese), where all the downtown's Lisbon streets have their buildings elevated view drawn. All the drawings are currently at the Lisbon's city municipal archive.

rebuild Lisbon's downtown and presenting the approved plans as well as all the instructions for its execution. Some noteworthy aspects could be mentioned regarding this decree. First of all, it starts by cancelling a law that was published at 3rd December 1755, practically immediately after the earthquake, banning the construction inside the limits established, under the penalty of demolishing those illegal structures (§1). This had the purpose of preventing the same fast construction done before the earthquake, giving time for the engineers to delineate a new plan for the city. Secondly, and a continuous mention in the document, was that all the buildings must respect the elevated views drawn by *Casa do Risco*, with very restrictive permissions for additional features applied on the façade walls (§8). Moreover, the building's maximum height was limited considering the top of *Terreiro do Paço* buildings the reference that could not be exceeded (§14). Thus, the original two story buildings idea was left aside, as previously said, being decreed that the number maximum of stories was limited by the total height of the buildings. In other words, the commercial areas at the ground floor would have a clearance height of 16 spans and, the remaining height would be equally divided. In practice, this resulted in a four floors buildings typology above ground as can be perceived in Figure 3.4. Also in this point, the type of windows was stipulated accordingly to the façade orientation and the floor. The first floor of all buildings facing the principal streets should have balcony windows, and the ones facing the secondary should have “regular windows” as well as the remaining ones of the other floors and façades. This law also stated the instructions for the streets and sewage construction (§15). The principal streets width was stipulated at 60 spans following the instructions given by *Manuel da Maia* in his dissertation. The main sewage duct – *cloaca* - should also be constructed beneath the major streets with 10 spans width and 14 spans of height. The landlords would also be responsible for the construction and maintenance of the streets (as well as the sewage duct) that confines with their buildings (§16). The secondary streets were also referred, stipulating their width in 40 spans, 20 for vehicles and 10 in each side for pedestrians (§18). Note that, in the secondary streets a sewage duct would not be constructed.

Lastly, the reconstruction plan not only focused on rearranging the streets in a different and improved manner, but also on the building architecture façade projects that all the landlords must respect and apply to their buildings accordingly to the street where they would be constructed. Although it is not directly mentioned in the previous, or other law documents, the building's façade was selected accordingly to the street classification or hierarchy. It means that a building constructed in a principal street would have a better and refined frontage architecture rather than a building facing a secondary street. The differences were subtle, but, despite that, significant enough to be noticed and to ornament the buildings, namely the ones erected in the major streets, where the changes in the windows stonework were easily perceived. The façades were not all equal and some authors divided the façades in types, like *Mascarenhas* who consider 6 (Mascarenhas, 2004), or *França* who assumed 3 generic types that when combined produced another 3 types (França, 1989). In this present work, emphasis to that discussion will not be given. What is important to cling to and take note, is that independently of the façade chosen for each building, the symmetric base properties or principles were equal for every construction made at the time.

It is also important to mention that a law dated from 15th June 1758 made emphasis that all the elevated views designed and presented to the landlords must be respected, leaving no room for modifications by the constructors.

Although many references in law documents were made to the exterior architecture of the buildings regarding their construction aspects, practically none were made related to the interior ones. However, one is mentioned in the previous referred laws - 12th June 1758 law at paragraph 9 – regarding the floor construction in the buildings. This one states that the floor pavement shall be constructed by spacing at equal distance timber beams that should be supported by the masonry walls.

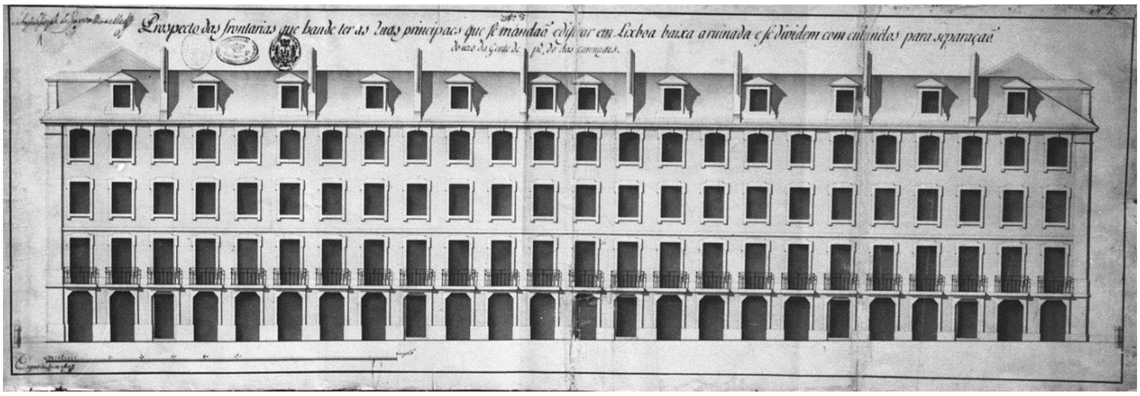


Figure 3.4 – Example of a *prospecto* to be applied in the main streets – Lisbon's city municipal archive (Cod: *PT/AMLSB/SER/S00517)*

CHAPTER 4

ANTI-SEISMIC CONSTRUCTION EVOLUTION

4.1 INTRODUCTION

Earthquakes and the evolution of constructions have been connected to each other for many centuries. The perception that some structures or structure modifications could mitigate the risk of collapse evolve year after year and, nowadays, a vast experience has been collected, from ancient structures examples to older construction regulation codes. Certainly, the earthquakes were, in the past, along with other natural disasters, the driving force that impelled architects and engineers to find solutions to overcome the negative impacts caused by these calamities and creating the opportunity to apply new city transformations, not only architecturally but also culturally. However, the social and economic repercussions related to this events are usually enormous. Not only they destroy infrastructures, property and material goods, but also social consequences are felt, like the fear felt by the populations for many years after. At the same time, the economic losses associated not only to the property destroyed, but also to the cost of rebuilding or construct new infrastructures is considerable, mainly if we are considering a trade city, like Lisbon was, that made commercial trades impossible to happen for a long period.

Until the 17th century, earthquakes were considered as acts of God, a divine punishment, thus closely related to the religion. For example, the reconstruction of cities in certain cases did not take place. Alternatively, a new city was erected in a new site, considering that the old city was, in some way, cursed. Some well-known philosophers like *Voltaire, Rousseau, Kant* and others, described this fatidic events and started to encourage that more should be done to better understand these catastrophes, that at the time usually caused an enormous number of deaths. Eventually, in the middle of the 18th century, some physicists begun to present theories to explain this events. Indeed, a turning point in history had started.

4.2 ANCIENT ANTI-SEISMIC STRUCTURES

The awareness that more could be done to withstand the horizontal forces caused by an earthquake, is not a novelty. Mainly, the ancient cultures found particular structural solutions to resist earthquakes. To make the point clear, in the course of past experiences they found that masonry “alone” collapse quite easily when submitted to horizontal forces, primarily due to the brittle rupture associated to this type of walls. Thus, the use of timber to reinforce walls was the symbiotic solution found and applied with success in many civilizations. This type of construction allowed a good structural response with using, generally, locally present resources (Lourenço, et al., 2014; Vieux-Champagne, et al., 2014). Therefore, the construction of walls with timber-laced structures started to be made, and many could be found today still erected, and with outstanding good conditions taking into account their age.

The first specimen of this type of structure ever found is dated from 79 AD. It was discovered by archeologists buried in pyroclastic flow from Mount Vesuvius when they dug up the port of Herculaneum in Italy. The structure, a two-story half-timber house, is one of the constructions described by *Vitruvius*[14] as the *Craticii* or *Opus Craticium* (Langenbach, 2007).

Other examples of this type of structures were found in many other countries like Greece, India, Turkey, which suffered many improvements overtime, usually at the same pace that the earthquakes or other natural disasters occurred. Each country had their own designation for this structures. For example, in India are known as *Dhajji Dewari*, in France *colombage, fachwerk* in Germany, half-timber in Britain, *himiş* in Turkey, amongst many others (Langenbach, 2007). Although, it is important to refer that all these had the same principle: the use of crossed timber members inside a typical masonry wall, reinforcing the walls for horizontal seismic loads. Even nowadays, this structures present an outstanding capacity to resist earthquakes, as demonstrated in recent large earthquakes like for example the ones that happened in Turkey in 1999, Greece in 2003 and Kashmir in 2005, where they had low levels of damage (Vieux-Champagne, et al., 2014).

Also important to mention is that even in countries like Germany, that could be consider non-seismic (i.e. seismic events hardly occur), this type of structures could be found proving that they were only not constructed for anti-seismic purposes at the time (Langenbach, 2007). Furthermore, it was not likely to find records or trace elements which indicate a general construction of this solution, proving that there was no legislative document forcing their construction to ensure the protection of citizens.

Besides that, and despite this structures had an excellent behavior when submitted to earthquakes forces, against fires the exposed timber becomes dangerous (Tobriner, 1999). This type of high flammable material could rapidly contribute for a rapid collapse of the whole structure,

---

[14] *Marcus Vitruvius Pollio*, also only known as *Vitruvius*, was a well-known architect and civil engineer from the Roman Empire. He is the author of *“De Architectura”*, known today as “The ten books on Architecture”, a book dedicated to Augustus Emperor and still considered as an encyclopaedia of construction nowadays.

and could fuel a fire spread throughout an entire city, as it happened in the past (for example the London's 1666 fire). Taking that into account, London's authorities in 1667 and Turkish authorities in the beginning of the 19th century, banned wood construction unless it was protected by bricks (Tobriner, 1999).

Portugal, like other countries in Europe, had this half-timber structures, mainly in the castle hillside, but it was no common practice to construct those. Therefore, only the landlords that wish to erect their buildings with such solution, have done it. However, a revolution in how the construction was made in Portugal happened after the great earthquake in 1755 that struck Lisbon city. This tragic event lead to the development and construction of the typical 18th century building: The Pombaline building (which will be later in this document explained and described in detail).

4.3 EUROPE DISASTER EVENTS AND THEIR INFLUENCE ON THE CONSTRUCTION CODES EVOLUTION

As it was previously mentioned, earthquakes, fires, and other natural disasters act as an impelling force to develop construction techniques and therefore reduce more and more the casualties that tragically happen in this kind of events. Nonetheless, there were events more remarkable than others, mainly due to the innovations made afterwards. Their influence in posterior rebuilding actions were important deserving therefore to be mentioned.

First, an event that, without doubt, defined the history of urban planning was the London's fire of 1666. At the time, London, just like others great cities in Europe, had a maze of narrow medieval streets. This has proven to be crucial for the fire spread that begun on September 2, 1666, in a bakery on Pudding Lane (Zack, 2015). The narrow streets made possible for the fire to spread from building to building crossing streets with almost no obstacle. To make matters worse, the timber construction used at the time promoted the fire that lasted for four days.

After the fire that destroyed 85% of London city, what remained were only the city ruins. Despite the tragedy, this event provided the perfect moment to apply a new and urgent urban plan in order to prevent this events to happen again. With this in mind, Robert Hooke only 2 weeks after the fire presented a new urban plan for London (until today there is no record of the referred document) but, it was the plan proposed by Christopher Wren that was submitted to discussion between the members of the government. This revolutionary urban plan had rectilinear and larger streets, thus, "organizing" the city streets layout, as it could be perceived in Figure 4.1. In spite of the innovative and better plan, it was not used. Instead, a document entitled "The Rebuilding of London act" was written in 1667, where a compromise was made to rebuild the city in a different and more organized way, rather than its ancestor.

But, regardless of the plan was not put into motion, it cannot be considered as useless. The main ideas and innovations made to the city served as inspiration to do the same in events that followed, like for example the 1693 earthquake in Sicily, Italy.

Another important fact about London's reconstruction, is that the use of timber was forbidden unless protected by bricks (chapter VII of "The Rebuilding of London Act"), claiming that the brick is not only durable but also safer against fire. Other actions worth mentioning were:

- The streets near River Thames was raised higher by three foot at least, in order to prevent inundations (chapter XXXIV of "The Rebuilding of London Act");
- All the landlords that lost property in the city's benefit were compensated for it (chapter XXV of "The Rebuilding of London Act").

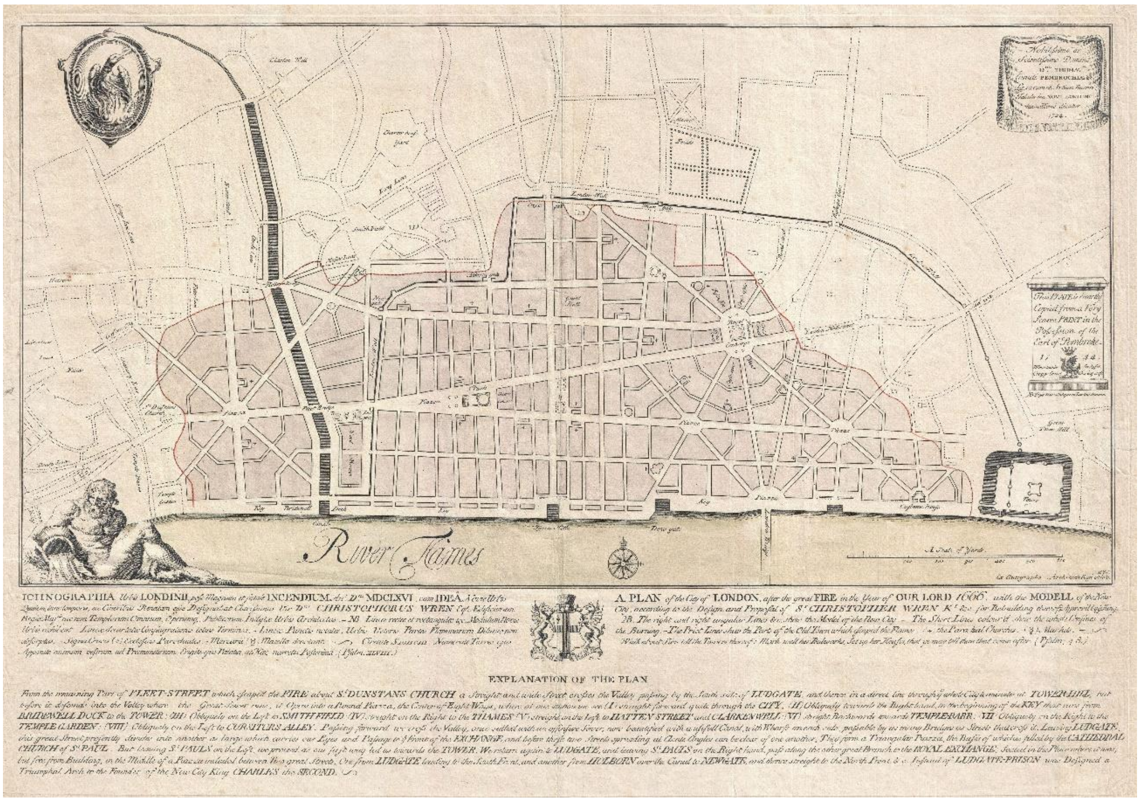


Figure 4.1 – Christopher Wren urban plan proposal for London after the 1666 fire (Historic Urban Plans Inc. Ithaca, NY, USA)

The second event here described and analysed was the earthquake that struck Sicily, Italy, in 1693. This region of Italy is well-known by his seismicity and volcanic eruptions (Etna Vulcan) and on January 9th, 1693, an earthquake with 6.2 of magnitude cause a tremendous building devastation in the region Syracuse. Many of the houses were torn down and the ones that stood still had to be shored up due to the considerable level of damage. Under those circumstances, and to make matters worse, two days later on January 11th, another earthquake struck. This time with a magnitude of 7.4, it destroyed what was left over by the first one, causing a complete destruction of Etna's region. After that a tsunami engulfed with a huge effect between Messina and Syracuse. On balance, more than 50.000 deaths and a complete wreckage of various cities was the outcome of these devastating catastrophes (Branca, et al., 2015).

Like it was previously stated, these situations are perfect for implementing new reforms to cities. And that was what happened. Emphasis will be made to Catania's reconstruction. One of the cities devastated by this fatidic event.

After the earthquake, Catania was rebuilt according to a new urban plan. Like other major trade cities in Europe, the fast-growing population lead to an erratic way of construction, ultimately creating a city with narrow streets potentiate an easier destruction when hit by an earthquake making it even more vulnerable (Ligresti and Grasso, 2009). This, as it was previously many times referred in this document, was a common problem in European cities at the time. The solution found can be compared to an earlier solution presented and applied: London's rebuilding. Catania's reconstruction was made with larger streets together with a rectilinear layout that conducts to large public squares, like Wren suggested for the reconstruction of London. Thus, Catania new streets should have at least 8 meters of width and the number of squares increased (Ligresti and Grasso, 2009). Adopting this solution to rebuild Catania could be in some way consider as an anti-seismic strategy approach, due to the fact that many of the deaths could be correlated to persons that could not escape because of the collapsed building debris (Tobriner, 1980), or have seen their way out blocked.

However, and unlike it was made in London where some restrictions were made to the new constructions, in Catania, none were made. Henceforth, no anti-seismic structures were made to counteract the potential threat of another earthquake destruction. Instead humble houses purposely built with a small number of floors, could be considered an anti-seismic strategy at the time (Tobriner, 1980), hoping that it would be sufficient to withstand future earthquakes.

Note that the architectonic style of the buildings still found today in Catania[15] and *Val di Noto* region, is the baroque style and based on the style of Palladio, Inigo Jones and Vignola (Tobriner, 1982, p. 124).

Equally important to refer was the seismic event of 1783. Five consecutive earthquakes between February 5th and March 28th, reaching a maximum magnitude of 7.3, razed Calabria to the ground (Bozzano, 2011). Thus, as it was needed, a reconstruction succeeded. Although, this time a different approach was followed. The high seismic vulnerability of the region, allied with the need to overcome the destruction caused by an earthquake in the future, led to a change, and also a mark, in the history of seismic events together with an anti-seismic construction development. The Bourbon government, at that time, realizing the little level of knowledge had regarding anti-seismic construction, sent out researchers to the Neapolitan Academy of Science resulting, one year later, in the publication by *Giovanni Vivenzio* of "*Istoria e teoria de'tremuoti in generale ed in particolare di quelli della Calabria, e di Messina del MDCCLXXXIII"*. This covers the study done to the damaged buildings, resulting in a newly structural anti-seismic solution proposal for Calabria reconstruction designated by *Casa Baraccata* (Dipasquale, et al., 2015).

---

[15] Today, Catania's city centre is considered World Heritage by UNESCO, due to its unique architecture.

This anti-seismic solution consists of a building with one or two story height, regular and symmetric. The resistance to earthquakes came from the timber structural frames with crossed members[16] (as could be perceived in Figure 4.2) that were in-filled with clay or stones. All the timber would be protected from the natural elements due to the fact that a plaster surface or mortar was applied on top, and when that was not the case, interwoven canes were fixed being covered by an earthen plaster (Dipasquale, et al., 2015). Also important to mention is that this invention was not a total novelty, since similar structures had been built in Italy previously to the 1783 earthquake (Galassi, et al., 2014). What caught the attention of researchers to those buildings was that they had minor damages comparing to the ordinary masonry buildings, which conducted them to develop and improve the construction technique.

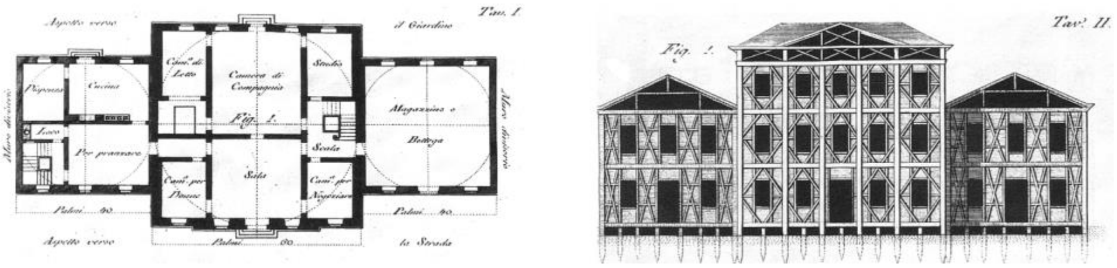


Figure 4.2 – Anti-seismic structure *Casa Baraccata* (Vivenzio, 1783)

After the reconstruction, the buildings where the *Casa Baraccata* (or *Borbone* constructive system) was applied had their first test against the earthquake horizontal forces in 1905 and 1908[17], passing with only negligible damages (Galassi, et al., 2014).

These seismic events previously described represented what could be consider as the most important ones due to the innovative ideas implemented and, consequently, served as a starting point for other reconstructions and innovations all over the world.

4.4 POMBALINE RECONSTRUCTION: THE FIRST ANTI-SEISMIC CODE

In light of previous chapters, Lisbon's 1755 earthquake was also an equally important event that is impossible to overlook. Surely, it was a mark in Portugal's seismic events history, causing tremendous losses not only in human lives but also in properties, as it was explained before. Even though, the benefits to seismology and to civil engineer construction were incredible for the time. In this chapter, a comparison between the events described in chapter 4.3, and Lisbon's 1755 earthquake, will be made, along with an explanation of why *Pombal's* actions and plans were so relevant, leading to what could be considered as the first anti-seismic code for construction.

---

[16] Saint Andrew wooden crosses.

[17] 1905 and 1908 earthquakes that strike Calabria reaching a top magnitude of 9 (Dipasquale, et al., 2015).

In the first place, the set of immediate actions (see chapter 3.2) taken by *Pombal* could be perceived as civil protection measures. The *Pombal's* well-known phrase "Bury the dead, and take care of the living ones", represents clearly its commitment to restore Lisbon's normality, restoring all the safety conditions for the population along with the commercial trades that were so important at the time for the economic prosperity of the city. As it was previously mentioned, the inquiry done to the population is also, unquestionably, an important piece in seismology history. Thirteen questions were present in that inquiry, and the main objective was, for the first time in history, to understand the physics beyond an earthquake event. A turning point was established in the seismic science, leaving aside the divine and God's punishment theories, as several philosophers had suggested.

Coupled with all those actions, was the plan delineated by *Manuel da Maia* and the central piece, the Pombaline building allied with the *gaiola pombalina*. This structural system, that granted an anti-seismic resistance to the building was not a new invention at the time. Like other countries in Europe, this type of structure was being used, but not directly for structural anti-seismic purposes, and landlords were free to apply the technique to their buildings, i.e. there was no construction obligation of the technique. Though, what was noticeable (in Portugal as well[18]) was that those structures did not had significant damages after an earthquake. Thus, the Portuguese studied and developed these structures with a new purpose: forcing the construction, by law, of this structural anti-seismic solution, therefore ensuring the safety of all the citizens in possible coming earthquake events. This is the turning point in history, where a government obliged the constructors to apply an anti-seismic solution. Note that, some building restrictions were made in London and Calabria, namely in London where the use of brick was mandatory in order to prevent fire proliferation[19]. Although, in none of the past events prior to 1755, nothing was made to ensure the citizens protection in the new constructions, regarding seismic damages.

Also relevant to mention is that this solution is often compared with the *Baraccata* system previously explained. However Calabria measures after the earthquake allied with *Baraccata* system is considered, by some authors (Galassi, et al., 2014; Tobriner, 1983), as the first seismic code to be applied in construction after an earthquake, others (Langenbach, 2007; Scawthorn and Chen, 2002, p. 582), state that building regulation could be traced as far as the measures taken by *Marquês de Pombal* after the 1755 earthquake. This discussion and divergence of opinions is valid since, until today, no physical evidence of a regulation was ever found in Portugal of that time, but, the most compelling evidence is that all the buildings constructed in Portugal during that time had, as structural solution, the *gaiola pombalina*. Also quite noticeable is the similarity between both of them. Despite the fact, the typical Pombaline building had a four story height (Pinho, 2008), comparing with the maximum of two constructed with the *Bacarrata* system.

---

[18] In Lisbon's Castle hill-side some half-timber structures built prior to the earthquake stood still with little damages after Lisbon's earthquake.

[19] Note that in Lisbon's reconstruction the prevention against fire proliferation was also ensured, protecting all the timber structure framed, as it will be better described in the next chapter.

Regardless that, the main point is both *gaiola pombalina* and *Casa baraccata* were the first anti-seismic structures developed exclusively after an earthquake devastation, in order to prevent the same tragedy to occur in future events.

Quite extraordinary is that, today, the seismic regulation is based on the same principles used by *Marquês de Pombal* and the nominated engineers at the time, during the development of the *gaiola.* It could be said that the main goal of any seismic code in the world is not to avoid the loss of property or create indestructible buildings, but is to design structures that could withstand the ground movements induced forces with a level of damage that made possible for any person inside to escape safely to a safe zone (*FEMA 313 - Promoting the Adoption and Enforcement of Seismic Building Codes: A Guidebook for State Earthquake and Mitigation Managers*, 1998). Therefore, it could be said that the basic rules for any building design prepared to endure an earthquake is to have a linear geometry and/or symmetry plans along with a reasonable height, allied with a construction based on ductile materials (*FEMA 313 - Promoting the Adoption and Enforcement of Seismic Building Codes: A Guidebook for State Earthquake and Mitigation Managers*, 1998).

By the same token it is stated that any building code is established considering three relevant aspects: experience basis, theoretical basis and designer judgement (Scawthorn and Chen, 2002). Comparing now with the Pombaline construction code, the similarities are evident. First of all, the development and improvement of the timber cage solution (*gaiola*) was done after the observations done to earlier constructions with a similar technique (half-timber) that had resisted the earthquake, as it was mentioned previously. Therefore, what happened was an evolution in the construction technique enhanced by previous practical experience.

Secondly, the theoretical basis. Despite the term “theoretical” this is not only related to theory, but also to experiments in laboratory, or others, that can corroborate the effectiveness of a certain technique or theory. Hence, and comparing again, it is known that *Carlos Mardel*, had successfully tested a real-scale model in *Terreiro do Paço* with a battalion simulating the seismic horizontal forces. The objective was not only to test the structure that had been developed, but also, to show a “visual proof” to Lisbon population the importance of this technique in the reconstruction.

At last, what could be considered as the knowledge acquired from past experiences by the designer: designer judgement. Put differently, over time the engineers acquire the capability to analyze rapidly the efficiency of a certain technique applied in a particular situation, mainly due to previous experiences. In Lisbon, the group of engineers nominated by *Marquês de Pombal*, were certainly a valuable asset, considering the past experience in construction to the Portuguese kingdom at the time.

To sum up, and given this explanation, *Marquês de Pombal*, could be consider as the cornerstone of all the development in anti-seismic building codes after 1755. His example lasted for generations until today, due to his first civil protection measures along with the development of, what may be regarded as the first anti-seismic structure and code, being his utmost concern the population’s safety.

CHAPTER 5

THE POMBALINE BUILDING

5.1 STRUCTURAL SYSTEM – *GAIOLA POMBALINA*

The structural system of the Pombaline building is the key element that gave to this type of building the earthquake resistance needed to overcome another catastrophe similar to the one of 1755. In the beginning *Manuel da Maia* suggested in his dissertation only a two story building construction that combined with the large streets would provide a safer environment to the population making possible for them to run away to secure zones. However there is nothing mention in his documents how the structural resistance of those buildings would be made. Then, when the decision to construct four floor buildings came into action an effective structural system became urgently needed. Thus, a solution was found: erect the buildings in a timber cross system that joined to outer envelope masonry walls conferred to the global construction the so needed resistance to an earthquake scenario. Despite the lack of originality[20], this idea was improved and enhanced when the city's reconstruction started.

There is no record at all when this improved solution started to be implemented, as well as in all the urbanistic laws published at the time, none of them made any reference to this brilliant invention. However, and possibly due to the complexity of the system to be solely by one person, it is common to attribute the implementation of this solution to *Casa do Risco* and their engineers at the time. Other documents refer to *Carlos Mardel* as the inventor, mainly due to his experimental tests done in *Terreiro do Paço* to a similar structure there constructed and tested by a military battalion (França, 1989).

Prior to the earthquake, all the buildings were erected in masonry heavy walls conferring almost no resistance at all to the building. This type of construction was proved not to be the best solution for a city like Lisbon, with a significant seismic activity history. Thus, the '*gaiola'* solution became

---

[20] Prior to the earthquake, this structural solution was applied in some constructions around the Lisbon's castle area (Mascarenhas, 2004).

the answer to those problems, making it possible to build four story height and, at the same time, provided the structural resistance desired. This was possible mainly due to some particularities of the conceived system. The major one was the lightness of the timber when compared to the old masonry walls. It is known that the mass of a building plays an important role regarding the seismic effects, thus, a timber structure would drastically reduce the weight of the building which combined with the cross timber members conferred an increased resistance that could not possibly be achieved with a simple masonry wall. Another feature of this solution is that the existing masonry walls that create the building outer envelope were reinforced with timber crossed members equal to the ones used in the interior's building. This constituted an improvement of the resistance of those walls that protected the timber from the outer elements. Lastly, other crucial detail could be pointed out: all this elements were interconnected, working as a single mechanism. In other words, the pavement, the inside and the outer walls, which constituted the structural system, were all interconnected.

The '*gaiola pombalina'*, as it is known in Portugal, could be described as an interconnected group of timber members that combined had an exceptional response to horizontal loads. The vertical elements – *prumos* - are the longer ones of this system. They go across the entire floor and were blocked by horizontal members – *travessanhos* – that were placed between them. Interconnecting the notches and complementing this frame were two (or one) timber member(s) displayed in diagonal. All the characteristic connections of this system will be better explained in a following chapter focused on this matter.

To sum up, this new construction technique could be divided into two distinctive parts: the exterior, that corresponds to the masonry walls, and the interior made by the interconnected resistant timber structure. This symbiotic relation produced what is known today as the Pombaline building.

5.2 PREFABRICATION APPLIED IN LISBON'S RECONSTRUCTION

Lisbon's reconstruction, in the beginning, had many problems conditioning the normal course of the works. Many workshops were destroyed due to the 1755 earthquake and the lack of specialized construction workers to produce and apply the components needed represented a serious threat to meet the deadlines imposed. Thus, the high demand for specialized manpower to respond to these labour requests, allied with the urgent need to reconstruct the city impelled the establishment of a new method to overcome those problems, and, in a certain way, manage the resources available with extreme efficiency. Despite the difficulty inherent to this endeavour, a brilliant solution was conceived: pre-manufacture all the basic construction elements. This solution transformed the construction works at the time, in a way that specialized teams were assigned only to manufacture a certain element and no contact existed between the manufacturer and the constructor[21]. Therefore, those teams, and because they only made one type of

---

[21] All the construction elements were sold in a kind of stock market for building materials. In other words, the government acquired the products, and then sold them. This not only made the buying process easier (one

construction element, could improve their production rate significantly. Also, all the houses would have the same type of materials and the same dimensions, thereby allowing the buildings to have all the same aspect desired by the King. Being all the buildings constituted of the same construction elements, the Pombaline architecture contributed significantly to the adoption of the King's will.

The particularity of this pre-manufacture method consists on a modular system, i.e. the pieces were produced as single elements. Therefore, their combination permitted to erect a building in a much simpler way. With this, various scenarios could be covered and the reconstruction became more versatile. But not only exterior elements were produced this way. Interior ones like tiles[22], floor stone cladding, and others were sold this way. Also important were the nails that had a great contribution in connecting all the '*gaiola' timber* elements together, accelerating the process. An example of the nails used can be seen in Figure 5.1.

Figure 5.1 - Example of the nail used in the Pombaline buildings exhibited at *Museu do Dinheiro – Banco de Portugal*

Pre manufacturing this standard size pieces also brought another great advantage: no special tools or specialized workers were needed on the construction site. This had a major impact due to the previously mentioned lack of specialized workers at the time, making possible their application by anyone even with a limited experience in construction.

5.3 CONSTRUCTIVE TECHNIQUES

There were numerous techniques applied in the construction of this type of buildings. However all of them were in some way similar to each other and based on the same principles. This present chapter does not attempt to explain all of them, but expound only the common ones and their underlying principles that inspired the development of analogous ones. In contrast to the elevated

---

place had almost every construction products needed) but also prevented the price to inflate as it is characteristic of times of crisis.

[22] They were applied on walls, mostly in kitchen areas or stairs.

views streets projects that every landlord should obey, it also important to mention that for the inside construction of the buildings scarce references, if anything, could be found regarding the application of a specified construction technique(s).

5.3.1 FOUNDATIONS

The Pombaline building foundations were a quite clever system. Taking into account that the construction was made on top of a ruined landfill with alluvial soils beneath, the solution applied provided the stability needed. The chosen solution supposed to deal with this low bearing soil capacity was similar to what is known today as a foundation pile or to a micro pile. In other words, green pine piles with a length of approximately 1,50 m and 15 cm thick (Mascarenhas, 2004), were driven into the soil and then connected top to top (horizontally) by other pine members – logs – using pegs and/or nails, as it is depicted in Figure 5.2. After the piles were spiked on the soil and the horizontal logs placed, another horizontal timber elements, this time placed perpendicularly to the first logs positioned, served as foundation for the masonry walls.

However, their conservation was at risk because timber elements would rot naturally after a few years. But, since they were not exposed directly to the natural elements and as they were spiked in a humid environment (due to the alluvial soils) they would last for years, and thereby their conservation was ensured.

Figure 5.2 – Pombaline foundation timber piles exhibited at *Museu do Dinheiro – Banco de Portugal*

Several foundation solutions using this previously described pine piles were implemented throughout Lisbon’s downtown reconstruction. However, two major ones were preferred: the isolate and the mat foundation. In the first one, the piles were placed aligned with the structural bearing elements (main walls and columns) and the isolate foundations were connected between each other by a solid brick arch, as could be perceived in Figure 5.3. Moreover, between those arches, vaults were constructed, and on top of those, filling material was placed to fill the gap and equalize the ground floor. The main goal of using this system made with vaults and arches could be directly related to the excavation(Appleton, 2011). Put differently, this structures not only distribute efficiently the loads at the ground floor, conducting them to the centre of the foundation, but also contribute to reduce considerably the terrain excavation considering that the soil between the direct foundations would not have to be all removed. It is also important to mention that this type of system had, in some way, a mixed solution, specifically, the columns would have isolate foundations, and the exterior walls of the buildings would have continuous foundations, all interconnected by arches and/or vaults.

But a slight difference can be noticed between column and wall foundation. While the wall is founded on a base made out of stones meticulously cut and arranged to maintain an equal gap between each single stone, the column was founded on large and single stones that were placed directly on top of the logs which were connected to the piles. Note that the columns could also be founded in a wall similar to the ones made to support the exterior walls. In both cases, and at ground level, the columns would be erected preferentially in blocks of stones that were placed on top of each other using a male-female connection system (Mascarenhas, 2004) (see Figure 5.3).

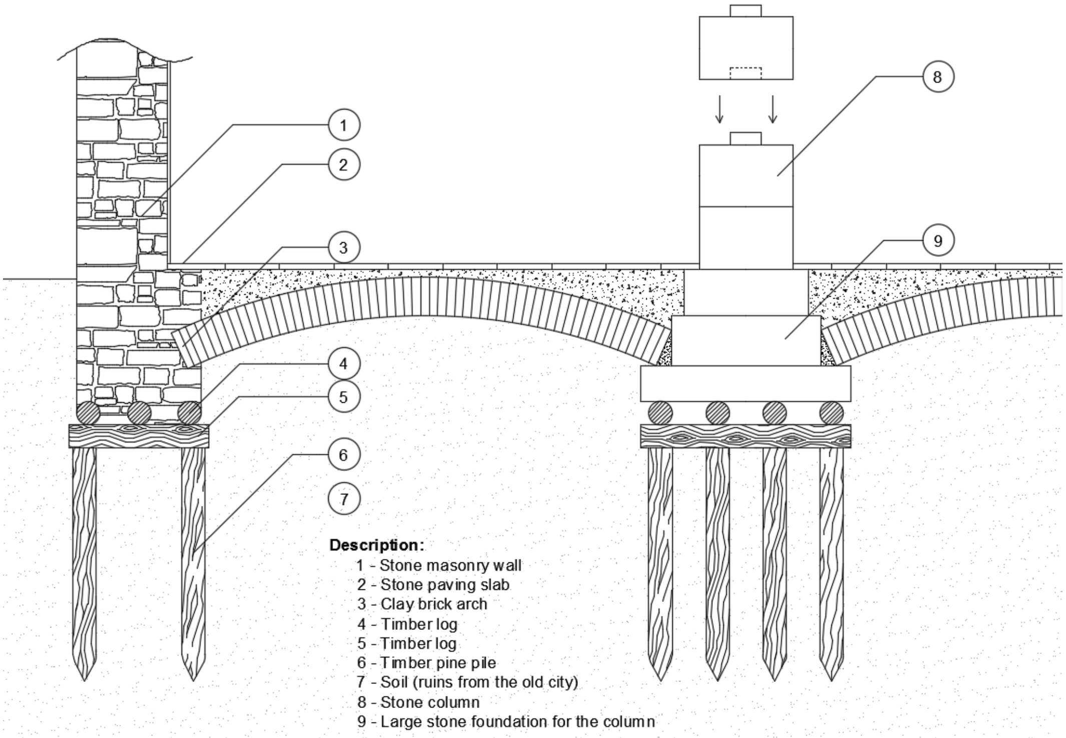


Figure 5.3 – Schematic representation of isolate foundations type of the Pombaline buildings (Adapted from (Mascarenhas, 2004)).

The second type can be comparable to a mat foundation. In other words, within all the area occupied by the building, piles were spiked and connected on top with crossed logs as it is represented in Figure 5.4. In this type of foundations, walls and columns share the same foundation, and the solid brick arches presented in the previous solution, would not exist.

An important fact must be mentioned in this chapter too: some researches (M. R. P. Cardoso, 2002) show that the pine piles used in this type of building foundations did not have such an important role in structural support as it was thought. The constant fluctuations in the groundwater level submitted the piles to dry-wet cycles which consequently caused them to rot. However, no structural consequences were seen due to that. It is thought that the piles placed in such close pattern (40cm from each other (Ramos and Lourenço, 2000)) not only helped to spread out the load in the terrain, but also had a huge contribution, as any pile spiked solution had, in consolidating the soil. Also a pine pile with only 1,50 m of length, would not reach the bed rock or any soil with bearing capacity, supporting the previous statement.

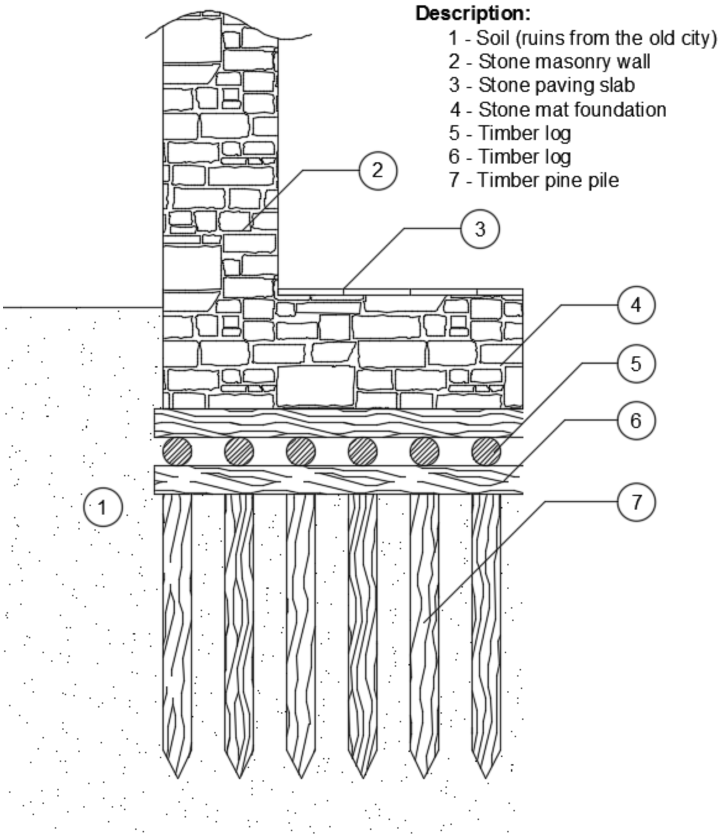


Figure 5.4 – Schematic representation of a mat foundation type of the Pombaline buildings (Adapted from (Mascarenhas, 2004))

At last, and illustrated in Figure 5.5, is a variation from the first solution in this chapter referred. This one intended to reach deeper soils and, for that reason, larger and profounder clay brick or stone piers were constructed to support the building and the top masonry foundation walls. The construction of the columns was quite similar to the one previously presented, although this time the single large stones were not used. Instead of it, masonry walls were erected from the bottom with bigger rocks.

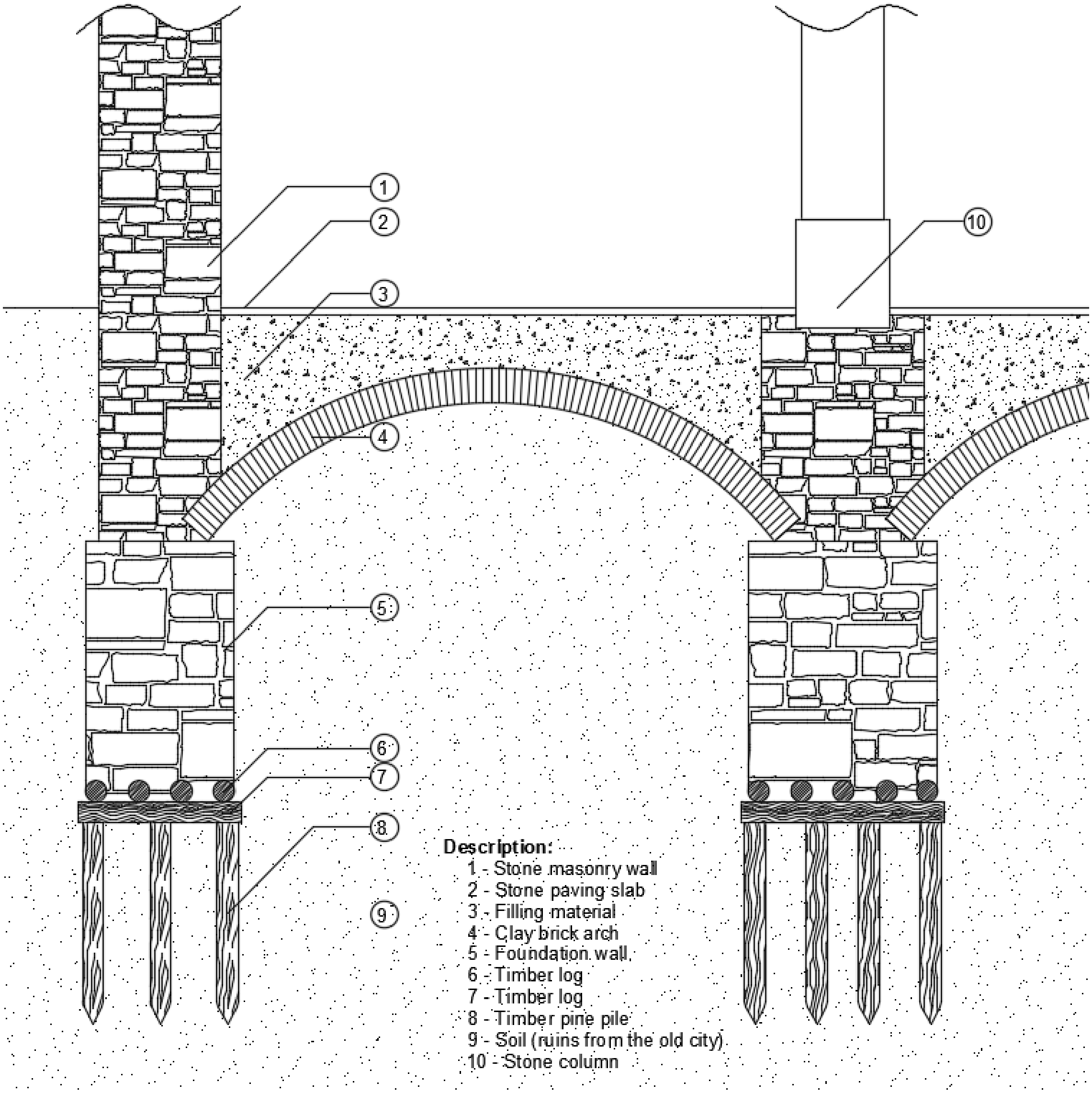


Figure 5.5 – Schematic representation of deeper foundations usual in the Pombaline building construction (Adapted from (Appleton, 2011))

5.3.2 GROUND FLOOR

At street level, the ground floor aimed mostly for commercial purposes. The open spaces and the austere architecture are the main characteristics of this floor. The easy access to the street along with almost no obstacle inside has given to this area tremendous possibilities. Several commercial areas cropped up in the main streets being the secondary ones occupied with stables and barns.

This floor is clearly different from the other ones in structural aspects. No timber members were added to increase the structural resistance, and thereby, stone arches along with rigid stone columns take place to give the structural safety needed to this open space. This option had other major effect, it prevented the timber members to be in contact with water or ground ascending water and consequently, the *gaiola* only rises up from the top of the arches being water isolated extending its longevity. Also important to mention is that this arch solution, similar to the one that was adopted in the foundations, is a brilliant way to dissipate the loads throughout the entire base of the building, and therefore, supporting the upper floors properly.

The stone paving slabs along with the stone block columns contributed to the austere characteristic architecture. Still, a slight variance occurs from building to building at this floor according to the street where the construction was erected and the type of commerce that would be established there. Thus, two main solutions could be found. The first solution, mostly applied in secondary streets where the storages and stables were common at the ground floor, had between the stone arches a quadripartite brick vault, as could be perceived in Figure 5.6.

Figure 5.6 - Example of a quadripartite brick vault

This vault intended to better receive and distribute the loads to the near walls or columns and consequently to the foundations. On top, these were filled up until a levelled floor was obtained, so that in a following stage the timber pavement beams could be properly placed. An important feature regarding this solution was that this vault along with the stone applied all over the floor had an important effect preventing the fire from spreading to the upper floors. Thereby, fire could be easily contained and fought in the ground floor without affecting the remaining superior areas of the building.

The second solution, similar to the previous one presented, did not have vaults between the arches. Instead of it, timber beams were equally spaced and placed on top of the arches in order to support the first-floor pavement, as could be seen in Figure 5.7.

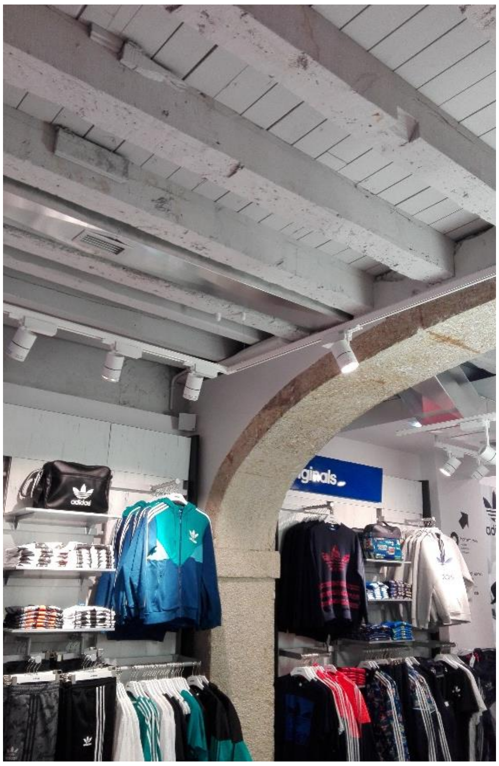


Figure 5.7 – First-floor supported in stone arches

It is important to mention that this solution, represented a weaker seismic resistance due to the fact that only the arches and the timber beams that supports the first-floor pavement connected to the columns and to the main walls and façades. Therefore, an uniform distribution of loads could not occur. This was a very common solution since it could be constructed at a faster pace than the alternative one. In certain cases, the arches were only built parallel to the main façade, and the timber beams were placed perpendicular, supported by the façade and the arches.

5.3.3 *GAIOLA*

As it was previously mentioned, there is no official record of projects as well as the inventor behind this ingenious solution. However, it is meritorious all the woodwork and the assembly techniques applied during the construction of this structural system that can still be contemplated today, mainly due to the Portuguese vast experience in the shipbuilding industry. Thus, this chapter aims to explore and explain some of the major techniques applied in this type of timber cage, constructed inside the Pombaline building, to guarantee the seismic resistance required to ensure the population’s safety. It is also important to mention that, taking into account the long reconstruction period of time, the techniques displayed slight variants, possibly due to the improvement of the techniques during that time.

The *gaiola pombalina* consisted in interconnecting vertical and equally distributed members that go across the entire floor named *prumos*, with horizontal ones (equally distributed too) named *travessanhos,* that would block the first ones lateral movement. Complementing this, in the approximately square spaces created, timber crossed members – *escoras* – (St. Andrew crosses) would be connecting the notches, granting the resistance needed to withstand horizontal loads (Figure 5.8).

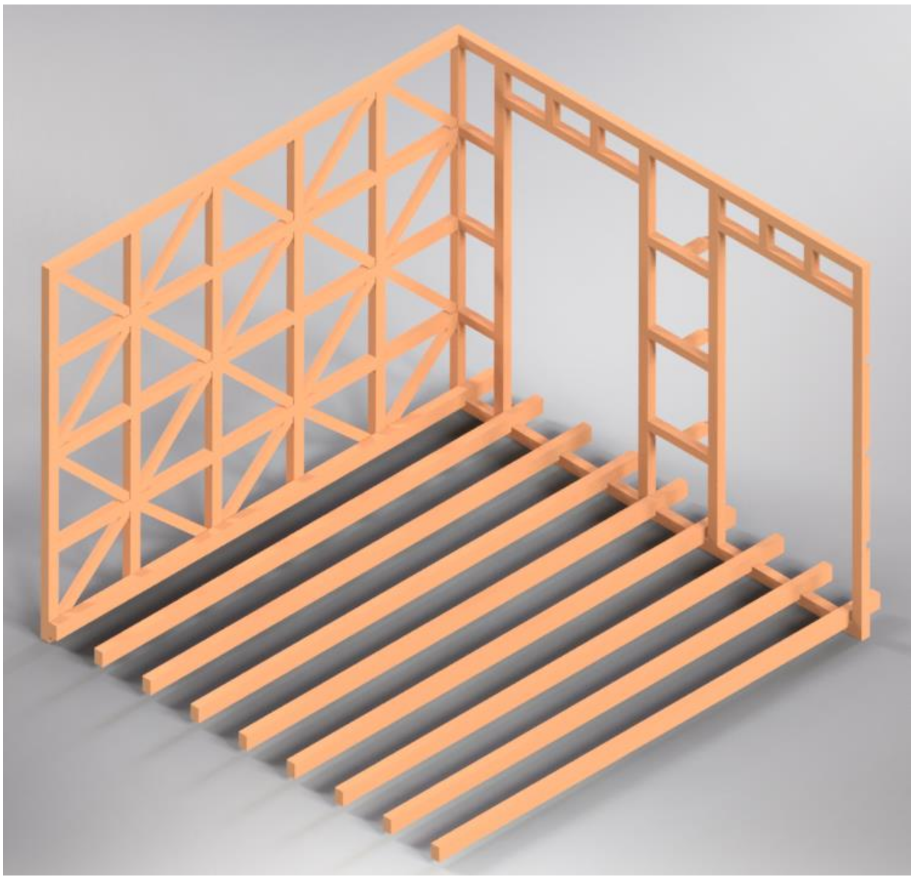


Figure 5.8 – Schematic representation of the timber Pombaline cage (Adapted from (Appleton, 2011; Mascarenhas, 2004)).

However, this timber cage was not equally constructed or assembled throughout the different blocks. Some differences could be noticed regarding the type of interconnections between the materials and the complexity of the system, according to the diverse areas of the building where it was being constructed. Also, the previous three elements mentioned (*prumo, travessanho* and *escora*) were not the only ones that made the construction possible, many others were applied and will be better described further into this chapter. Thereby, and for a clear description of the Pombaline cage it was considered (being aware of their differences) the next division proposal:

- Façade walls;
- Interior structural walls;
- Interior non-structural walls;
- Pavement.

First and foremost, it is important to explain the generic geometric lines of the cage primary elements. This elements had straight lines with approximately square sections quite similar to each other, evidencing slight differences from building to building considering the floor that was applied, as could be perceived below in Table 5.1.

Table 5.1 – Generic element dimensions [23] of the Pombaline cage (Mascarenhas Mateus, 2005).

Element [24]	**Dimensions**
Vertical – *prumos*	12 x 10 cm^2
Horizontal – *travessanhos*, *frechais, contra-frechais*	12 x 10 cm^2 (Upper floors)
	15 x 12 cm^2 (Bottom floors)
Pavement beams	12 x 16 cm^2
Diagonal – *escoras*	7 x 10 cm^2 (Upper floors)
	10 x 10 cm^2 (Bottom floors)

---

[23] Note that the dimensions previously presented in Table 5.1 may vary from author to author and/or on site. For example, *Leitão* (Augusto Leitão, 1896) states that the vertical members had dimensions ranging from 0,14x0,08 m^2 to 0,15x0,10 m^2. The option to pick out these ones presented in Table 5.1 is that they represent the average sizes that could be find *in situ*, and derive from a comprehensive research along with the numerous field tests conducted on Lisbon's downtown throughout several years, by a Lisbon's municipal work-team.

[24] Only the major and most used elements in the cage construction were mentioned in this table. Others, due to their specific application i.e. not so common throughout the timber structure, are not here specified.

Different types of wood could constitute this elements, being the most common ones the following: *Quercus pendunculata* (pedunculate oak)*, Castanea sativa* (chestnut tree)*, Quercus suber* (cork oak)*, Quercus ilex* (holm oak). It is also found in some buildings the use of *Larix decidua* (European larch) and *Pinus sylvestris* (Nordic pine) (Mascarenhas Mateus, 2005).

Still crucial to mention are some prevalent wood connections applied during the cage assembly of structural walls. Those were made mainly thanks to wood characteristic carved slots that allowed the individual pieces to fit in. Thus and besides the top basic butt joint, the most common ones are the dovetail half lap, half lap and mitred half lap (illustrated below in Figure 5.9). Although, slight variances to the ones mentioned could be found in particular cases. Complementary to this, after the elements were fitted together, and to guarantee a proper and permanent connection, a forged iron nail was hammered in almost every notch or interconnection. Further, the most common type of iron nail used was the *telhado* or *meio telhado* (Augusto Leitão, 1896, p. 297).

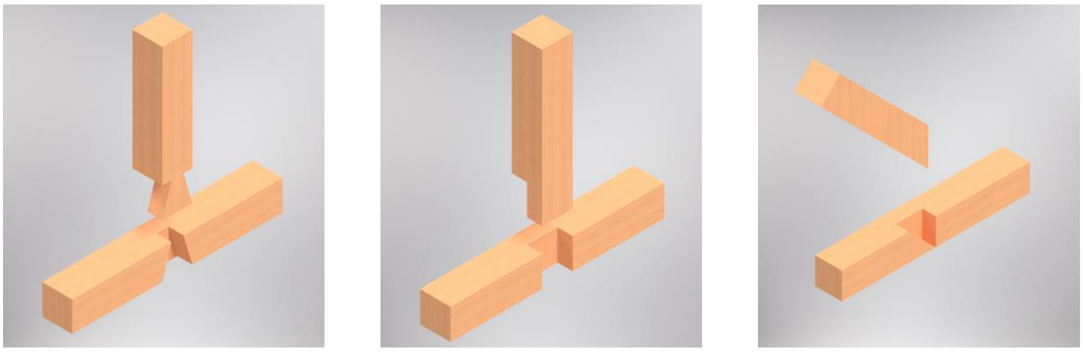


Figure 5.9 – Schematic representation of the usual wood connections types – From left to right: dovetail half lap, half lap, mitred half lap[25].

5.3.3.1 FAÇADE WALLS

The timber structure of the exterior façade masonry wall (Figure 5.10) could be considered as the simplest of all in the entire system due to the fact that the St. Andrew's crosses are not present, i.e. no diagonal members were applied. Although, and despite the apparent system simplicity, its importance cannot be obliterated in the overall structure interconnection with a perfect combination between the Pombaline cage and the masonry walls. Put differently, all the façade masonry that protected the interior of the building, were reinforced inward with the timber cage that was properly embedded in the walls[26]. This symbiotic relation protected the wood against natural environment elements also increasing in some way the structural resistance of the exterior walls.

---

[25] Very commonly applied in diagonal member connections.

[26] Note that the timber layout of the cage was not the same in all the masonry walls, being different if it was the façade or the fireguard wall between the buildings inside the same block.

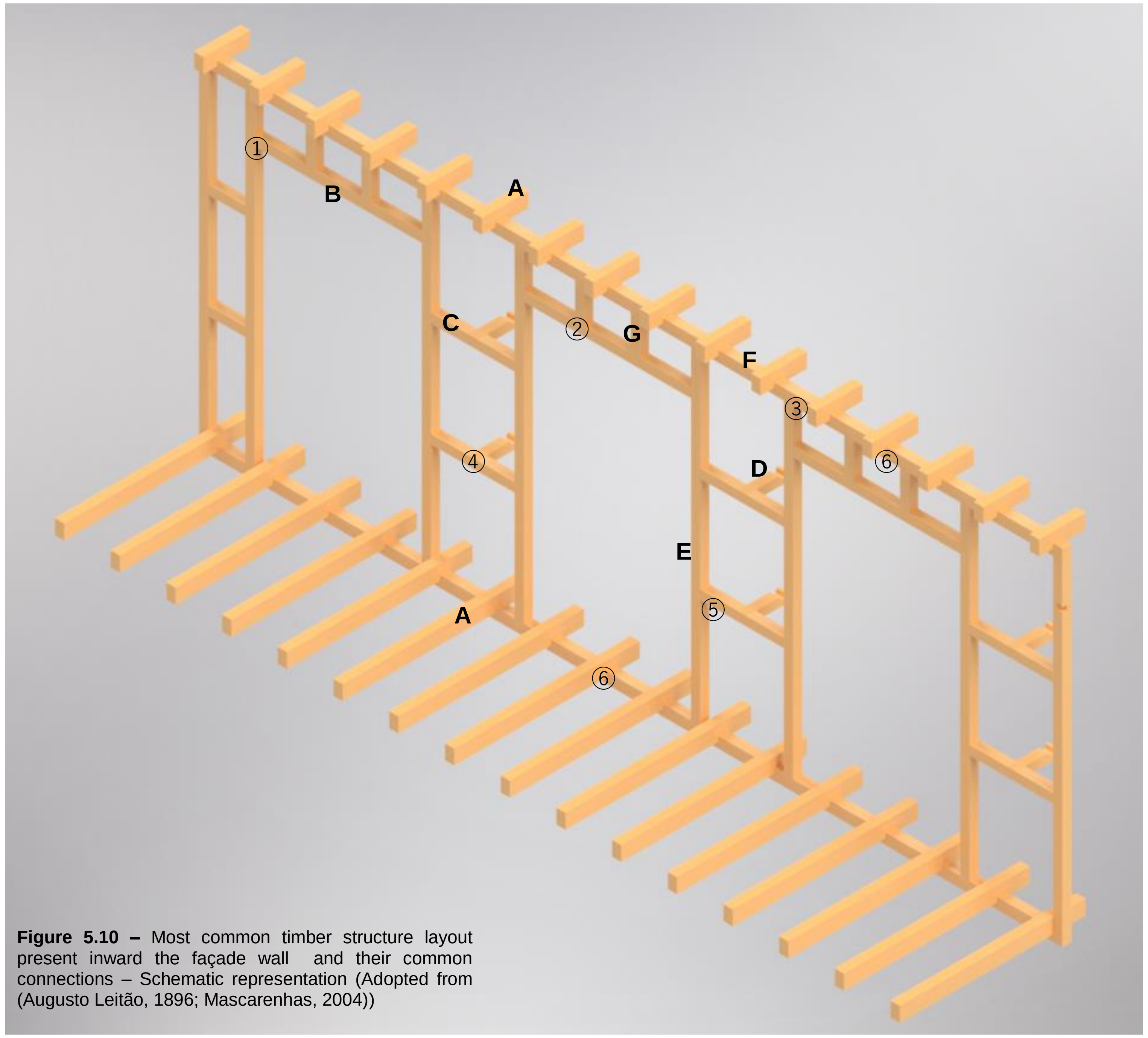


Figure 5.10 – Most common timber structure layout present inward the façade wall and their common connections – Schematic representation (Adopted from (Augusto Leitão, 1896; Mascarenhas, 2004))

Element description:

A – Pavement beam – these timber beams were fixed and supported on top of the *Frechal*. The usual connection between these two elements was made by a slot carved in the bottom top of the beam which allowed the connection. On top of these elements the floor wood boards were fixed. The top floor of the building had another element not represented in this figure, *Contra-Frechal*, which was placed on top of the beams. The main purpose was to connect all the beams and was a crucial element to place the roof timber elements properly.

B – *Verga* – Element applied to connect two consecutive vertical elements (E) when an opening in the masonry exterior wall was made for a window (for example). Also this element was fixed in placed by a dovetail half lap connection at the ends, and complementing at mid span of the piece, a *Pendural* (G) was applied to interconnect the *Verga* with the *Frechal*.

C – *Travessanho* - horizontal member that made the connection between two consecutive vertical elements – *prumos*. These ones not only block the vertical elements horizontal movements, but also connected the timber anchorages (D) to the masonry.

D – *Mão* – Element that connected the cage to the masonry wall. The connection could be done with a dovetail half lap, or half lap joint. This element was long enough to be embedded in 1/3 of the exterior masonry wall.

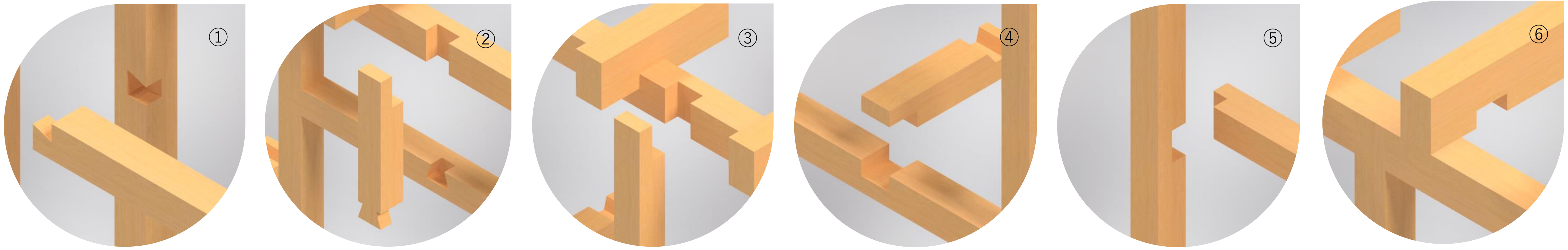
E – *Prumo* – Vertical element that go across the entire floor. To this wood element several pieces were connected - *Travessanho* (C), *Frechal* (F), *Verga* (B).

F – *Frechal* – Connecting all the vertical elements, usually with a half lap joint, this long horizontal member was the support for the pavement beams (A).

G – *Pendural* – Vertical element that interconnected the *Frechal* to the *Verga*. Usually the top connection was a half lap joint, and the bottom a dovetail half lap joint. The main purpose of this wood piece was to prevent the deflection of B.

NOTES:

1. All the assemblies represented in this figure are the most common applied during the Pombaline cage construction. However, other types or slight changes could be found, varying from building to building.
2. All the connections were complemented with an iron forged nail that was hammered to guarantee a proper connection.



The interconnection between the masonry and the cage was made with some special elements named 'hands' – *mãos* (Figure 5.11). Those wood elements were embedded in 1/3 of the façade wall (Mascarenhas Mateus, 2005), (Mascarenhas, 2004) connecting the masonry to the timber structure. They were fixed to the horizontal elements using both nails and wood joints, as it can be perceived in Figure 5.11. A different connection type where the 'hands' are joint to the *prumos* in diagonal is also possible (Mascarenhas Mateus, 2005, p. 125).

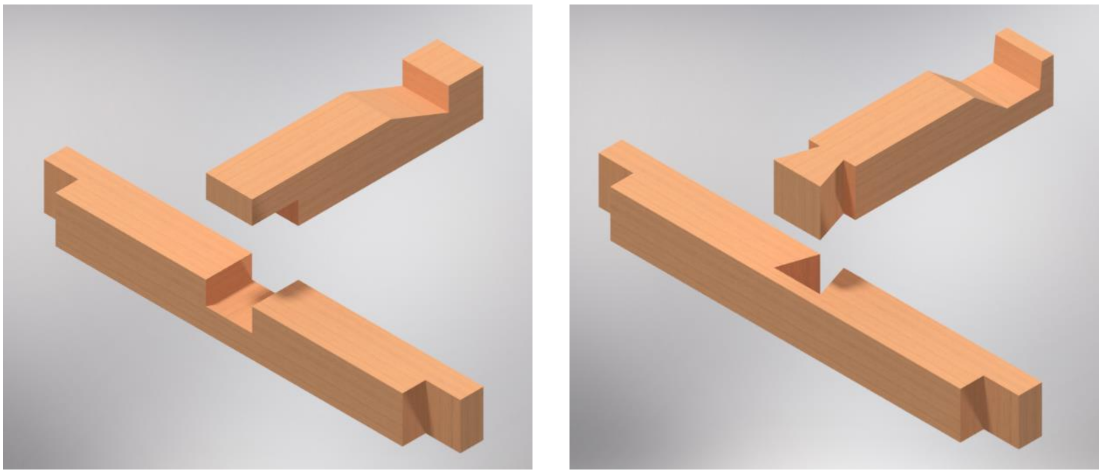


Figure 5.11 – Examples of the 'hand' wood connections – Schematic representation (Adapted from (Appleton, 2011; Mascarenhas, 2004),(Augusto Leitão, 1896))

Other special elements that have to be mentioned, are the iron staples used to ensure that the windows stonework would not detach so easily from the main structure (Figure 5.12) (Mascarenhas, 2004).

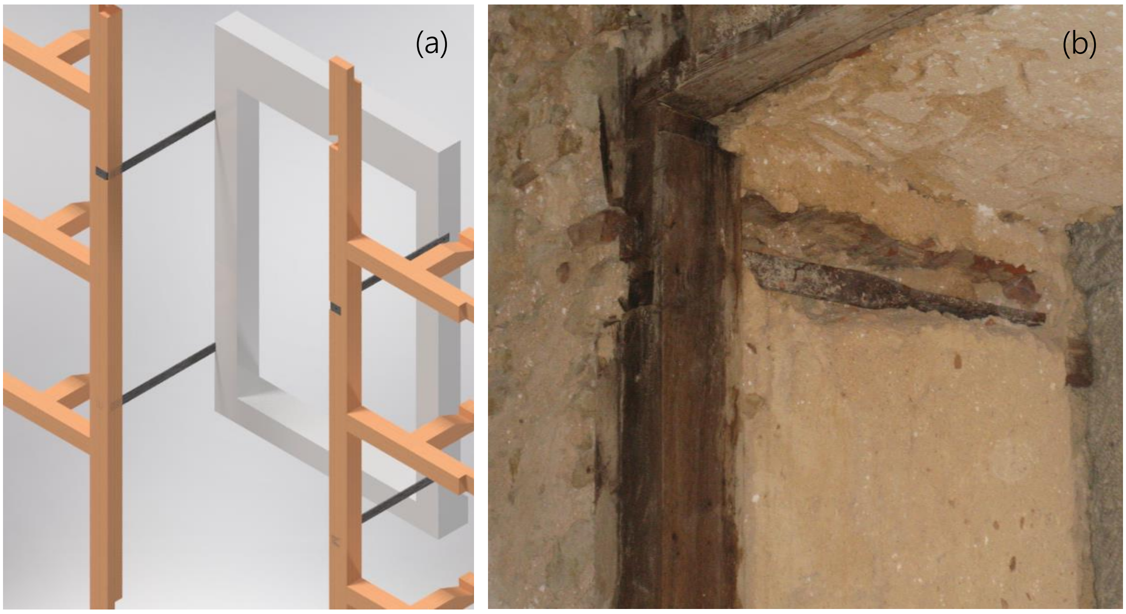


Figure 5.12 – (a) Schematic representation (Adapted from (Mascarenhas, 2004)) – (b) Real view - Window stonework anchorage to the timber cage

5.3.3.2 INTERIOR STRUCTURAL WALLS

Besides the timber frame placed inside the façade wall, another important part of this cage were the resistant or structural interior walls named *frontais* (example can be seen in Figure 5.13).

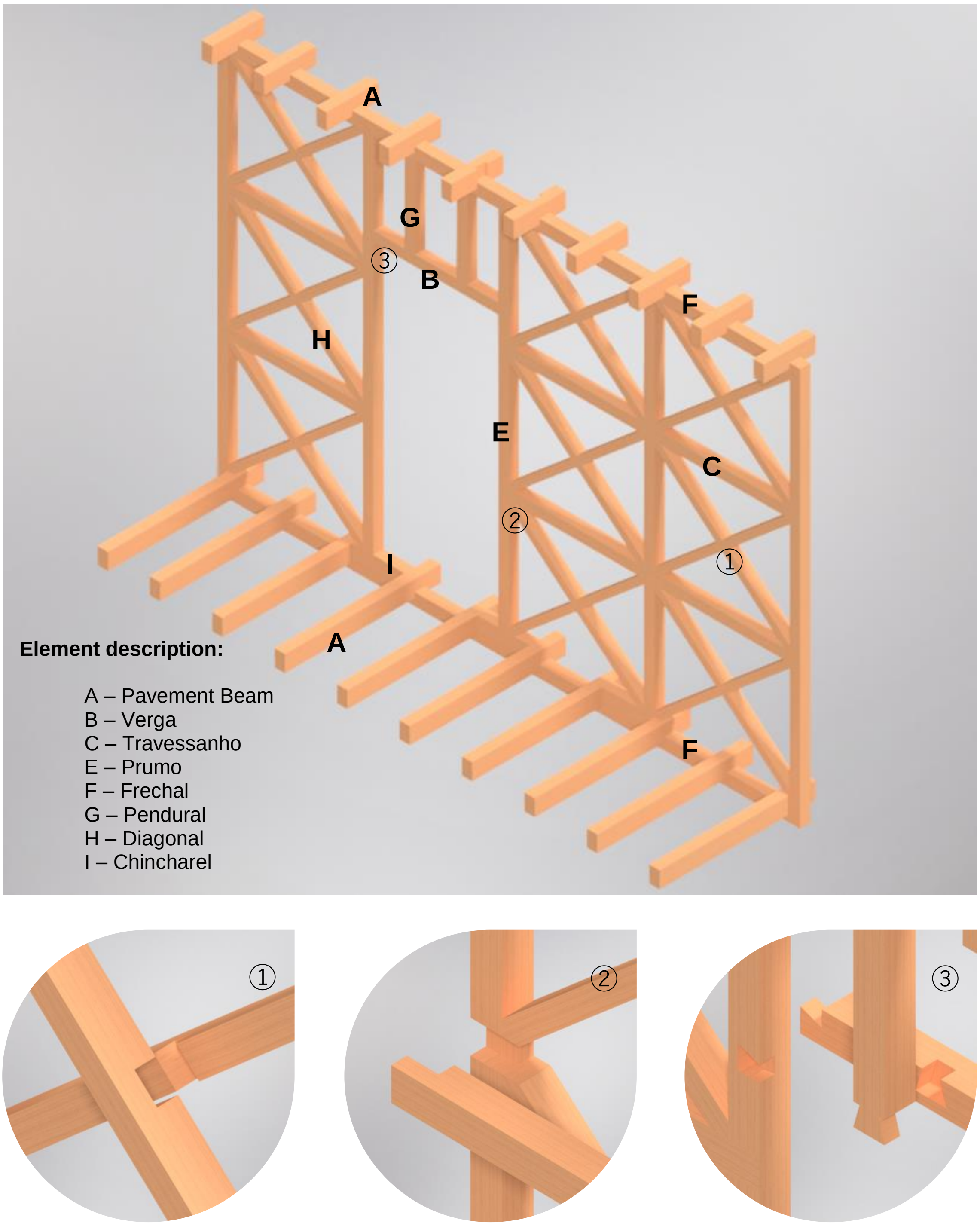
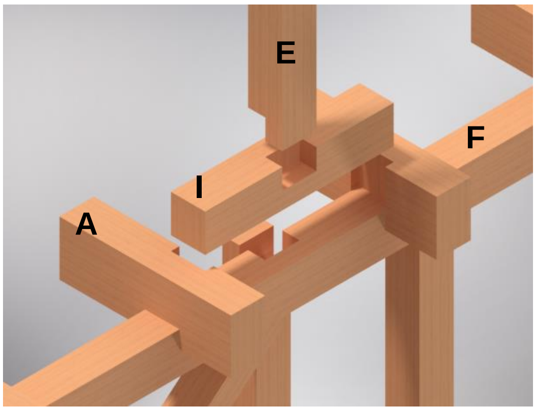


Figure 5.13 – Most common layout for the interior structural walls – *Frontais* – and their usual connections – Schematic representation (Adapted from (Augusto Leitão, 1896; Mascarenhas, 2004))

The vertical self-supporting timber frame was constructed by interconnecting vertical (E), horizontal (C) and diagonal timber members named *escoras* (H). Those well-conceived interconnections not only provided the structural resistance to horizontal forces, but also distributed the dead and live loads throughout the vertical elements, making sure that those are uniformly spread when they reach the foundations. This, in some way, could be explained by, not only, the correct alignment of the vertical elements, from the bottom to the top of the building, but also by the fact that all the vertical elements were embedded in the ground floor masonry (Mascarenhas, 2004). The vertical continuity was granted mostly by applying the solution illustrated in Figure 5.14. This was the most common, and consisted on carving a slot on the pavement beams besides the *prumo* (E) and a piece named *chincharel* (I) was fixed on top of the *Frechal* (F). This rare application of a third wood piece[27] made a new base for a proper connection of the consecutive floor vertical element.



Element description:

A – Pavement Beam
E – Prumo
F – Frechal
I – Chincharel

Figure 5.14 – Example of connection made to continue the vertical elements throughout the building – Schematic representation. (Adapted from (Mascarenhas, 2004)).

Symbiotically connected to this structural walls was the masonry that complemented this elements, blocking and confining the timber, while protecting it from the exposure to air and humidity. Usually made with lime, stone and/or clay bricks, it was in the free space between the wood members. Covering all the wall area, wooden slats were fixed in order to form a ground base for the application of stucco or other type of plastering mortar.

It is also important to understand that the construction of the Pombaline cage offered a construction method that could display some variants. In other words, the assemblies done by carving slots in the wood along with iron forged nails hammered, vary from building to building resulting in several types of panels. In addition to all the connections illustrated in this document so far, a few more are represented in Figure 5.15.

---

[27] Hardly, the connections were made using a third element.

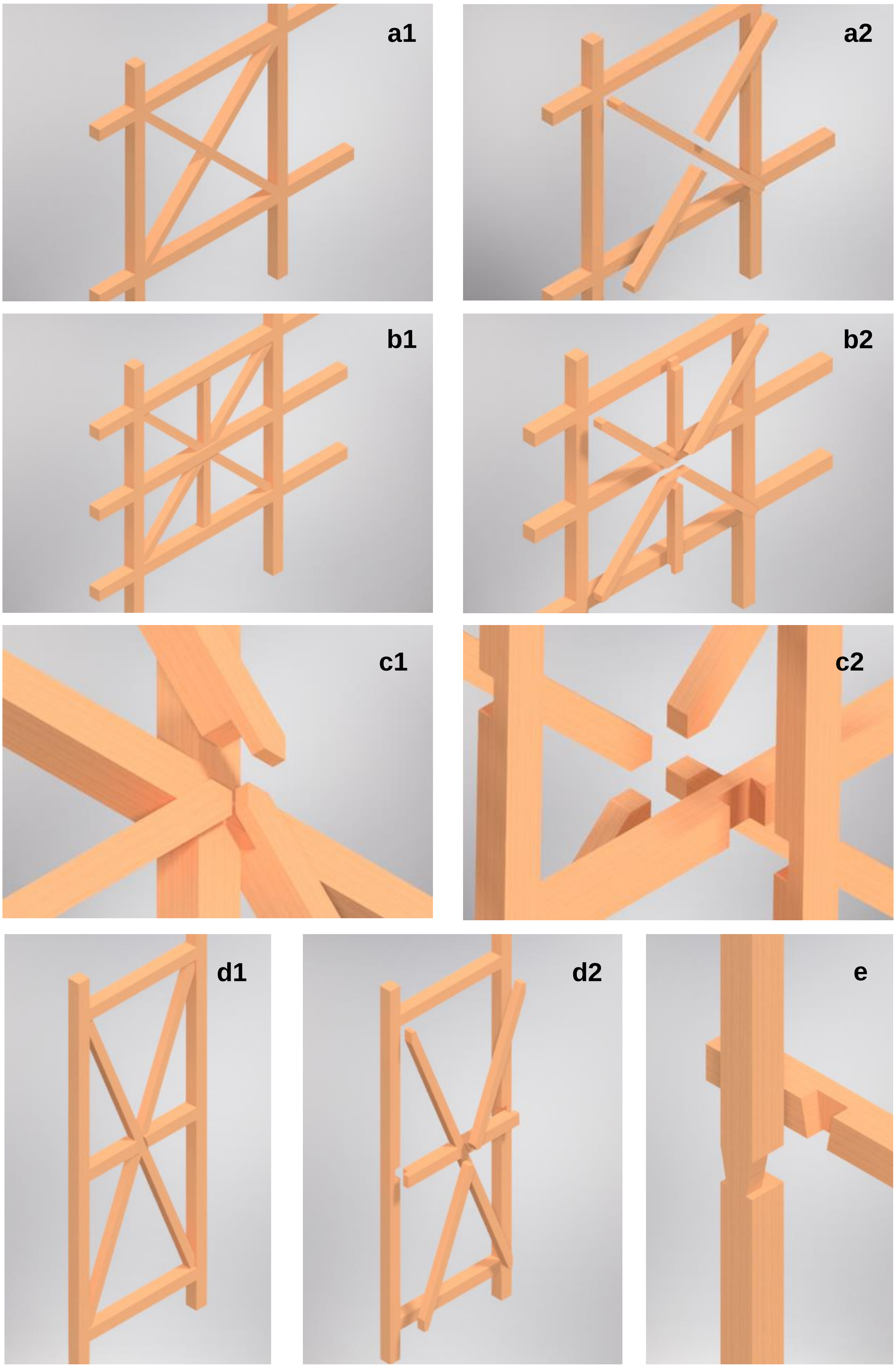


Figure 5.15 – Examples of structural walls (*frontais)* connections schematic representation (Adapted from (Mascarenhas, 2004)). – a1, b1, c1, d1 – Assembled view; a2, b2, c2, d2 – Exploded view; e - special connection used in interconnect prumos and travessanhos.

Also remarkable and worth mentioning were the inter-panels connections, that taking into account the structural integrity, were so relevant. The main objective of the construction of this cage, was to fit and interconnect all the members as good as possible. Therefore, in order to do that, “sharing” the same members when an intersection of panels occurred was the best solution possible. Although, due to architectural issues, sometimes that was not feasible and alternative ways had to be applied. In that way, generally, we could find three types of this panels interconnections in the Pombaline buildings: the first and conspicuous one was a vertical member – *prumo* - common to both panels; the second one consisted on adding a vertical member to the façade timber structure, in the same alignment of the interior panels, enabling the perfect and aligned connection; the last one is the “poorest“ connection that could be done and it consists of interconnecting only the horizontal and diagonal members. This last option was often made in short length walls (near interior doors for example).

5.3.3.3 INTERIOR NON-STRUCTURAL WALLS

Though, not only of structural resistant walls the cage was made, but also from non-structural walls too. These walls, designated by *costaneiras*, had a different layout where the diagonal crosses as well as the aligned interconnected vertical and horizontal elements did not make part of it. Instead, wood boards named *costaneiras* (O) were distributed vertically and fixed to diagonal elements named *aspas* (J) that also secured in place the vertical elements (named *gola* or *prumo* – M) that constituted the door wood frame. Similar to the other walls, a horizontal piece (N) would interconnect the two vertical elements between an open space for a door or window. Furthermore, and a crucial piece regarding the construction of this walls, was the wood slat fixed on the bottom side of the timber supporting beam (Q) that enabled the wood board fixation by nail. Along with this wood slat, the horizontal bottom element named *calha* (K), would had a lowered area where the board would be properly placed and also be fixed by nails. Below, in Figure 5.16 and Figure 5.17 a layout example can be seen.

This light weight and thin walls (comparing to the structural ones) usually did not respect any continuity from floor to floor or any special wall alignment at the floor. Also, their main application was to segregate small rooms. The wall finish, as it was made to the other walls, comprehended the application of wooden slats (P) equally distributed in height, with the same purpose as it was described previously in the other types of walls. Note that on the other side of this type of wall, wood slats would be distributed vertically spaced approximately at 20cm, in order to create a fixation support for the horizontal ones.

Supporting this wall, an additional timber beam was placed between the beams used to support the wood floor pavement. Their lateral movement was blocked by a secondary wood piece placed between the referred beams.

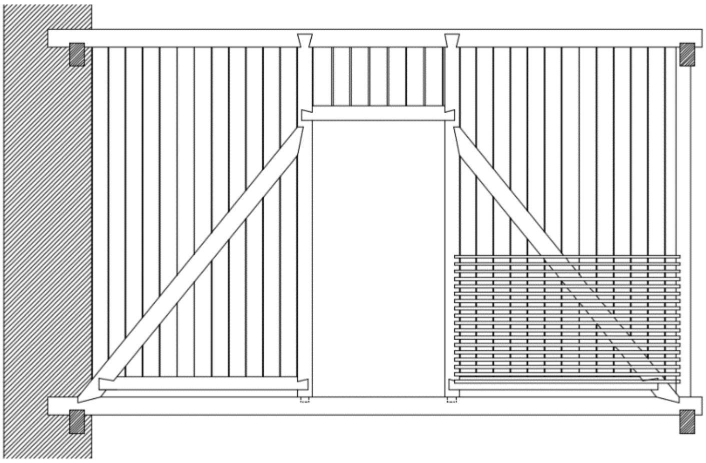


Figure 5.16 – General 2D view of the *tabique* wall

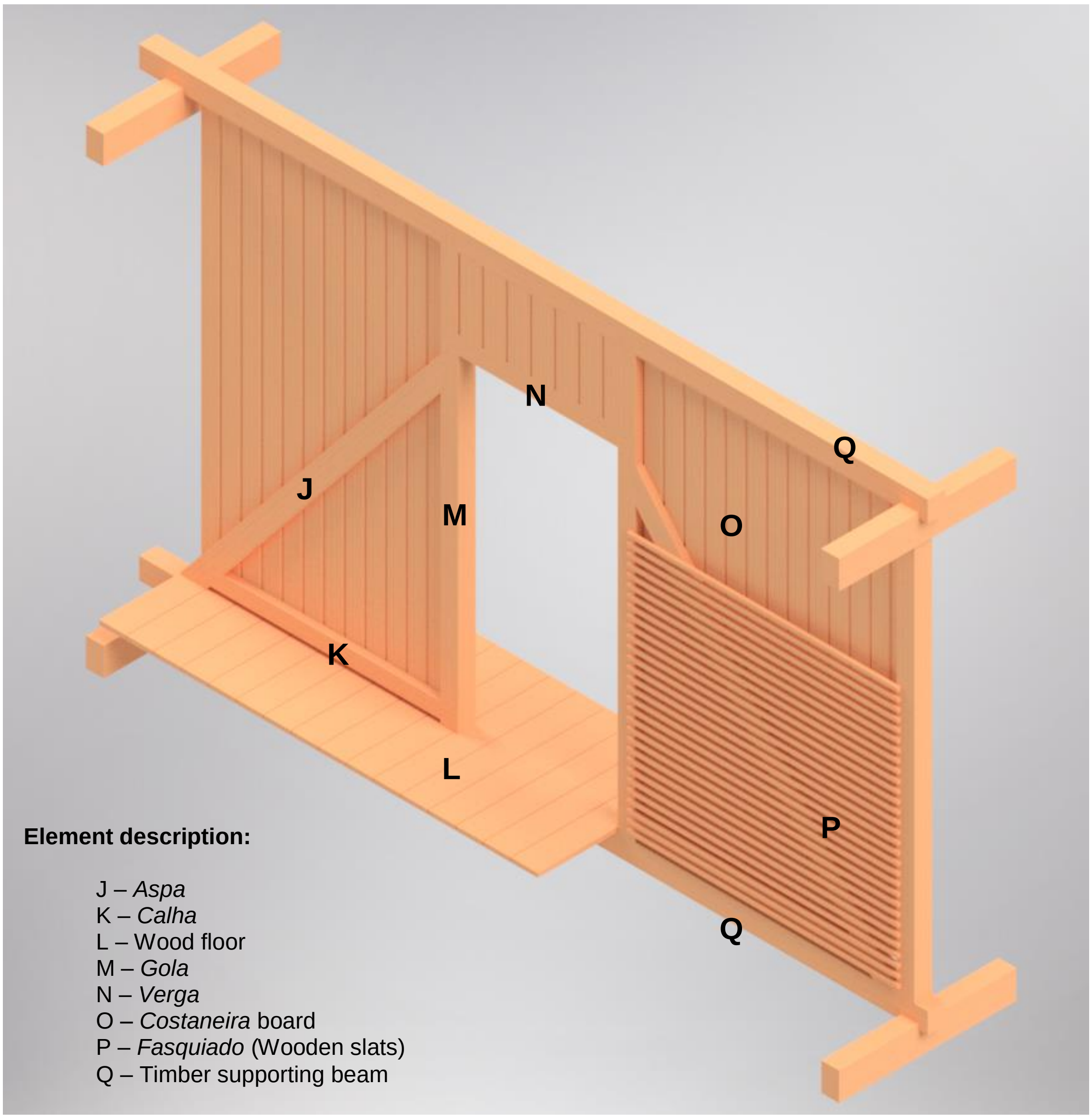


Figure 5.17 – General 3D view of the *tabique* wall – schematic representation

5.3.3.4 PAVEMENT BEAMS

In addition to the previously described types of walls that could be found inside a typical Pombaline building, it is now important to approach the elements that interconnect everything in each floor: the pavement beams. These horizontal elements are crucial not only because they join all the wall panels, but also because they have an important role regarding the transmission of lateral loads throughout the whole structure. Equally spaced, according to the supported dead and live load, in an interval range from 0.40 m to 0.60 m (Augusto Leitão, 1896), they were placed and fixed on *frechal's* top with characteristic carved slots (that will be explained and illustrated subsequently) along with nails.

Also, and in order to preclude lateral movements, it is common to find wood pieces, known by *tarugos* (R), in the space left by two consecutive timber beams. These blocking elements were pressed against the beams' lateral side and aligned perpendicular to the beams orientation as shown in Figure 5.18. To ensure that all of this pieces were well-pressed against the beams an adapted wood element was placed in the middle, known as *tarugo de chaveta* (S). This element had an opening that made possible the insertion of two wood chocks (T) which kept the alignment of the *tarugos* (Augusto Leitão, 1896; Mascarenhas, 2004).

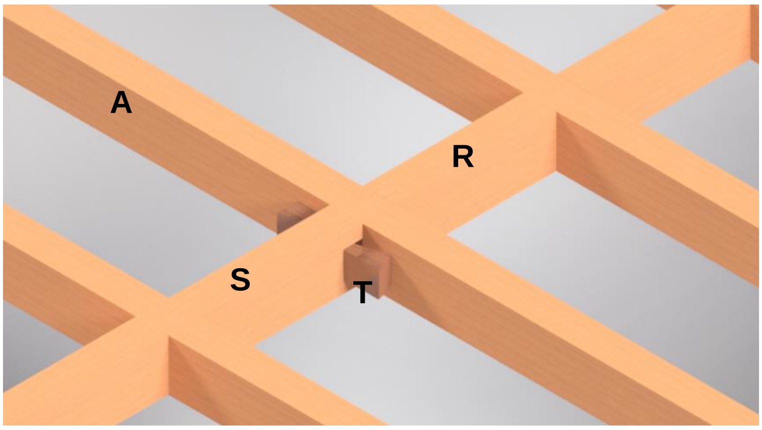


Figure 5.18 - *Tarugo* – Lateral movement block of pavement beams – Schematic representation – A – Pavement Beam; R – Tarugo; S – Tarugo de chaveta; T – Palmeta or wood chocks

Since these wood beams did not have an infinite length, thus, and in order to avoid weak points in the structure, some connection techniques were applied to ensure the continuity not neglecting the overall structural integrity of the Pombaline cage. These connections essentially were made by carving slots in the wood or making special cuts at the top section, (as it will be explained) making possible the perfect alignment between the connected members. Also, and similar to what was made in the structural wall notches, iron forged nails were hammered in this connections, in order to guarantee the correct assembly and to create a strong link between the elements.

The pavement beams were usually extended and connected on top of the interior structural walls permitting a better support for them. The assembly only had to make sure that the vertical loads were correctly transferred. Also, and to prevent lateral movements the beams were placed in carved slots, or if that was not the case, a wood piece would be placed between consecutive beams, for the same purpose (the combination of both could also be possible). It is important to mention that the first floor beams that are set on top of the ground floor arches and vaults had their lateral movements blocked by clay bricks placed between them. Some of the most common connections are illustrated in Figure 5.19.

.

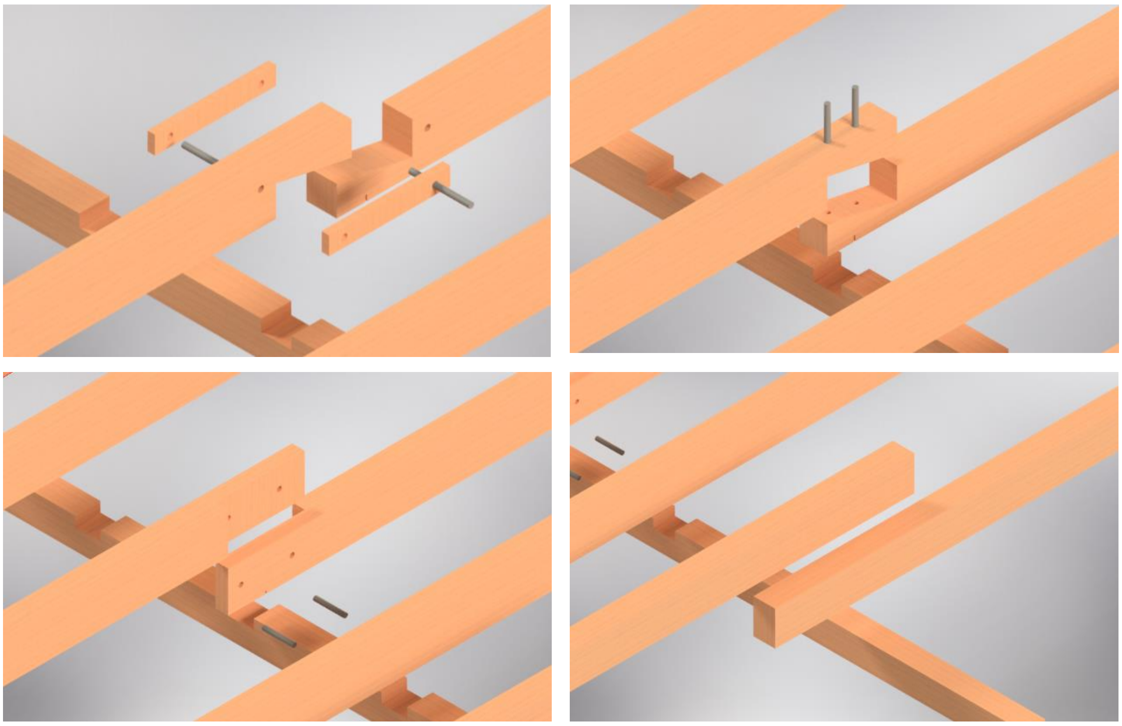


Figure 5.19 – Examples of usual pavement beam connections – schematic representation (Adapted from (Mascarenhas, 2004)).

Another relevant feature that could be pointed out are the iron forged pieces used to interconnect the beams to the masonry walls. Along with the previously mentioned wood 'hands', these elements had an important role bonding the interior and the exterior elements i.e. securing the timber structure to the masonry, resulting in a building all interconnected despite the different phase construction, as it will be explained afterwards. The interconnection was primarily made with the pieces represented in Figure 5.20 named *ferrolho de esquadro* (a) and *ferrolho de chaveta (*b) (Augusto Leitão, 1896). Each anchorage was fixed to the lateral side of the beam or to a groove[28] on the top, using nails passing through pre-made holes in the iron piece.

It was important that the anchorage remained free at the end, i.e., their fixation was done ensuring that sufficient length of anchorage would be embedded in the masonry.

---

[28] This groove ensured that no obstacle was in the way when the wood floor was installed.

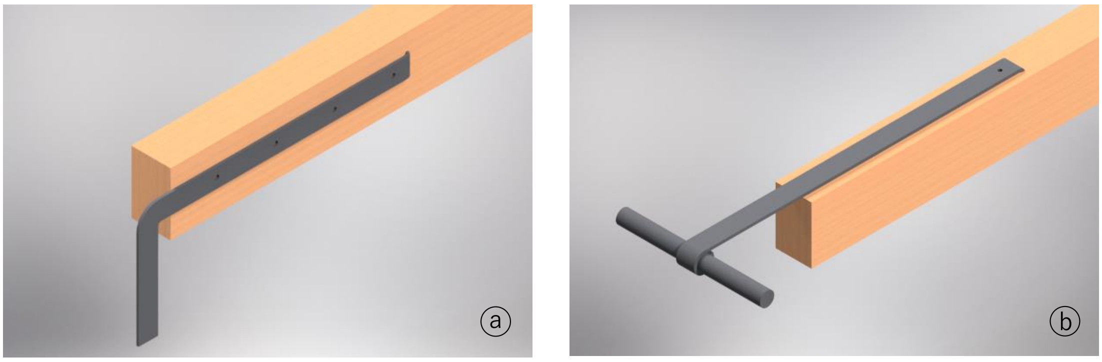


Figure 5.20 – Pavement beams types of anchorages to the masonry exterior walls – schematic representation – (a) ferrolho de esquadro; (b) ferrolho de chaveta - Adapted from (Augusto Leitão, 1896)

Note that the anchorage was not only done in the walls perpendicular to the pavement beams orientation. The anchorages represented in Figure 5.20 (b) were also applied to secure the beams (and in some way block their lateral movements) to the interior segregation walls inside the building block (see Figure 5.21).

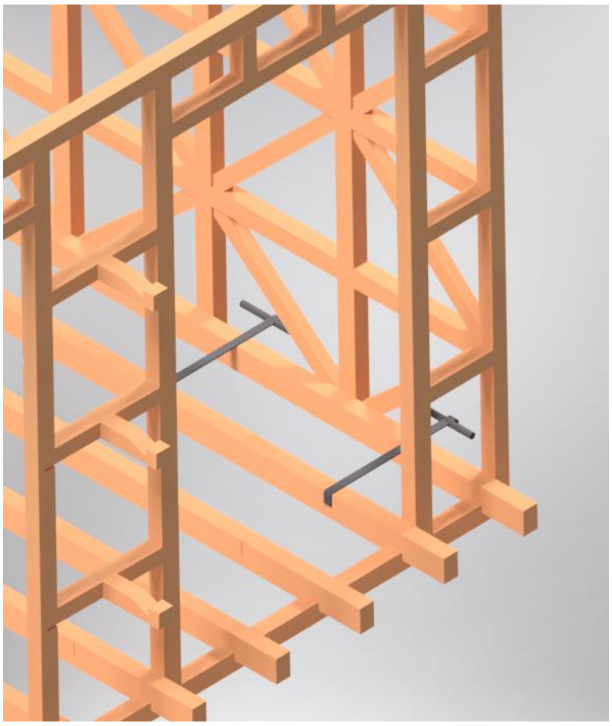


Figure 5.21 – Pavement timber beams fixed to the masonry walls with iron anchorages – schematic representation (Adapted from (Mascarenhas, 2004))

5.3.3.5 WOOD FLOORS

On top of all the timber beams were fixed the typical Portuguese hardwood floor made by a combination of individual wood boards that, all connected, would form the pavement for each floor of the building. The pine boards distributed along the beams (and nailed to them[29]), had a thickness that could vary between 24 mm to 36 mm, depending on the assembly technique applied and could have widths up to 22 cm (Augusto Leitão, 1896, p. 331).

The assembly techniques applied in the wood floor construction depended on the layout type pretended. Wealthy landlords would have wood floors and, consequently, house interiors better hand-crafted. Thus, the connections applied on those floors would be the best ones (Figure 5.22, connections 1 and 2 - half lap joint and male-female joint, respectively). The connection represented with the number 3 was the poorest one, essentially used in the construction of storage areas.

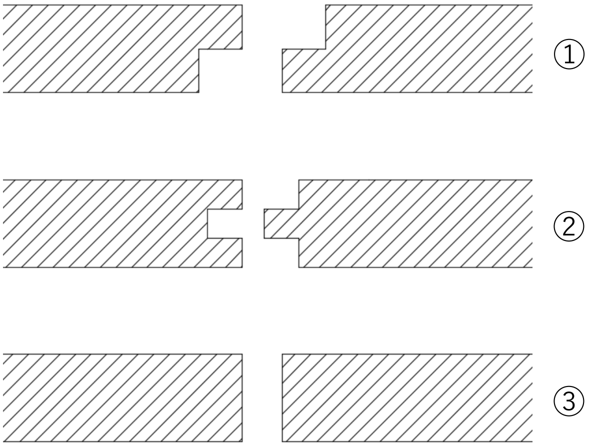


Figure 5.22 – Pavement schematic wood board connections – (1) Half lap joint; (2) Male-Female connection; (3) Top to top connection - Adapted from (Augusto Leitão, 1896)

Depending on the wood board distribution, several layouts could be done that sometimes gave a refined esthetical look. The major ones have characteristic Portuguese designations and were the following:

- *Soalho à Portuguesa* or *Soalho a meio-fio* or *Soalho de rebaixo*;
- *Soalho encabeirado;*
- *Soalho espinhado;*
- *Soalho à Inglesa* or *Soalho de macho-fêmea*;
- *Parquets.*

---

[29] The fixation to the timber beams was made with *meio telhado* nails.

The most common applied - *Soalho à Portuguesa* - is represented in Figure 5.23, along with its common connections and the techniques used to nail the wood boards.

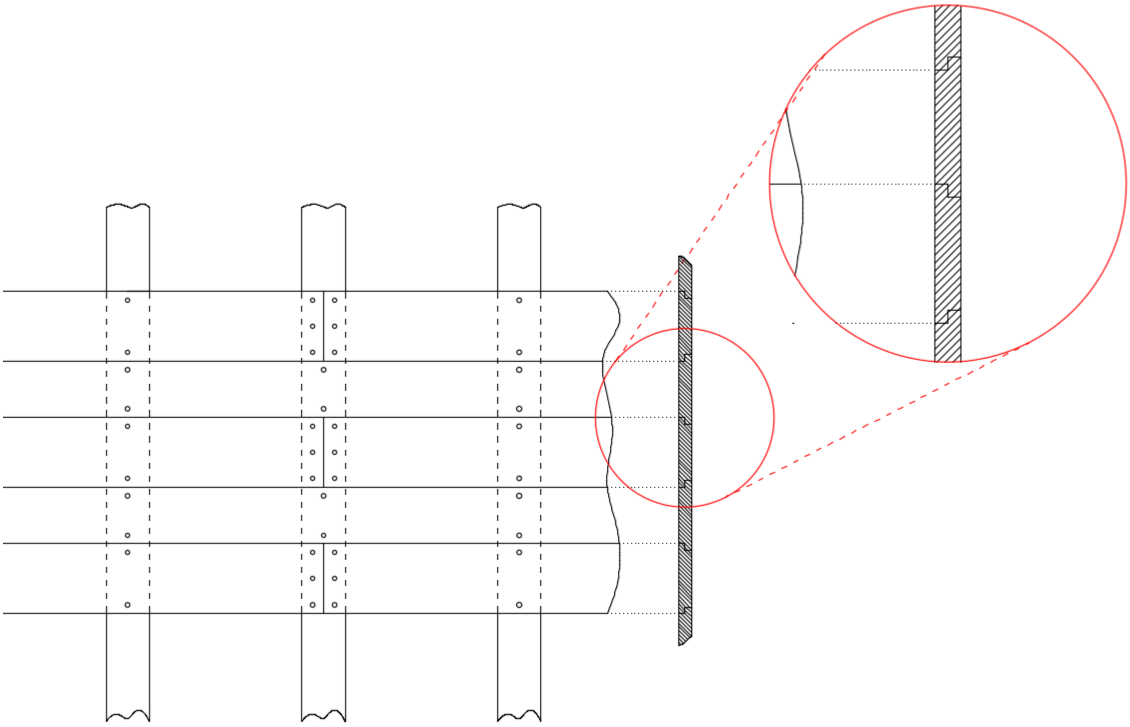


Figure 5.23 – *Soalho à Portuguesa* – Schemactic connections and wood board layout – Adapted from (Augusto Leitão, 1896)

5.3.3.6 CEILING

Covering the bottom of all the timber beams that supported the floor, was the ceiling. This could be made similar to the pavement (using wood boards fixed by nails) or it could be done in similar way that the walls were, applying a stucco on top of wood laths fixed to the beams. Not so often, and again in the buildings owned by wealthier landlords, hand-crafted ceilings in wood could be found, where the work done by the carpenters was quite noticeable. Part of this “last group” were the ceilings known as *tecto de artezões* or *tecto de caixotões*, where all the timber beams were left exposed, however never disregarding their proper garnishing.

The timber lined ceiling was, as previously said, constructed in a similar way like the pavement. Wood boards, this time thinner, were distributed and nailed with a lap between them. Consequently, other ones would be placed in those previous laps, overlapping part of the first boards. This common ceiling is known as *forro de esteira*, and slight variants could be found where the primary objective of those modifications were to garnish the ceiling. This situation is analogous to the choice between the *soalho à portuguesa* or the *soalho encabeirado*.

Apart from the timber lined ceiling, when it was intended to provide the ceiling the same aspect present in the walls, a stucco was applied. Therefore, wooden laths were fixed to the beams with a lap of 1 cm and all of them would have their top surface aligned and levelled as much as possible, as it can be seen in Figure 5.24 (Augusto Leitão, 1896, p. 371).

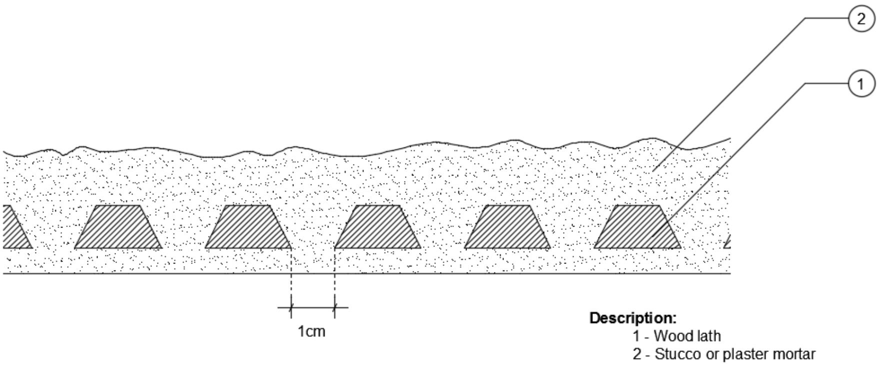


Figure 5.24 – Ceiling wood laths for stucco application – schematic representation

5.3.3.7 ROOF

The "last piece" of the Pombaline building is the roof top. They were quite similar from building to building although two distinctive types can be mentioned: the mansard and the triangular roof.

The mansard roof or French roof, could be directly connected to the purpose of obtaining more room in the last floor, taking advantage, as much as possible, of the building's construction area, while maintaining a simplistic, and at the same time elegant architecture, in the front façade. Therefore, the high ceilings are characteristic of these roof types when comparied to the other solution, enabling to better use the last floor. Below, a cut section can be seen, in Figure 5.25, as an example of this type of roof.

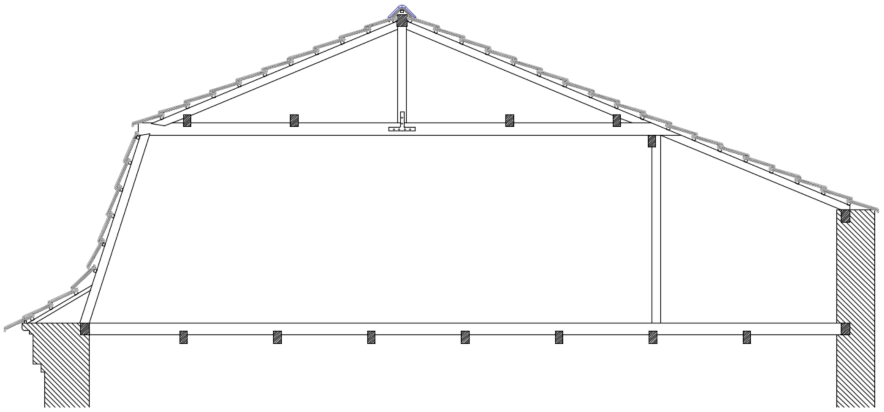


Figure 5.25 – Example of a mansard roof type cut section – Adapted from (Mascarenhas, 2004)

Note that, vertical elements were placed to connect the roof structure to the structural walls present in the inferior floor, therefore supporting it. In the course of time it was common to fix vertical elements to overcome the natural increase in deflection of the horizontal timber elements that supported the roof.

The second roof type applied in the Pombaline construction had a simpler structure rather than the previous one presented, where a simple truss was built. The triangular roof, did not intend to take advantage of the free room in the last floor, being a more straightforward solution. However, attic windows are present in this type of roof, and for them to be accessible, special structures were present in the interval of the triangular trusses. Below, a typical triangular truss is represented for better perception, in Figure 5.26.

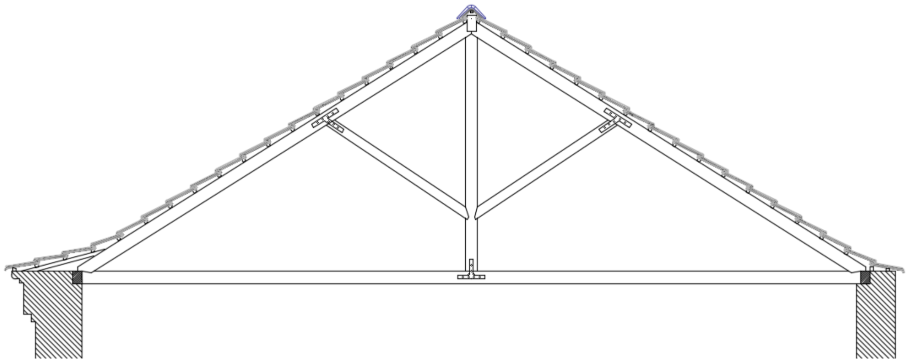


Figure 5.26 - Example of a triangular roof type cut section – Adapted from (Mascarenhas, 2004)

In this case, the trusses are only supported by the outside walls. However, vertical elements were placed too, in the course of time, for the same reason as it was done with the mansard roof.

In both cases, the interconnections between the elements that formed the trusses were made by carved slots in the wood in a similar way that the timber cage assemble was made. Although in the roof trusses steel plates were nailed in the notches, to ensure that the connections would stay in place over time.

Also regarding both types of roofs, it was standard procedure to cover the interior side of the roof with a timber lined ceiling known as *guarda-pó*, usually with the application of boards of a lower wood quality when compared to the wood used in the other floors ceiling.

5.3.4 POMBALINE BUILDINGS – OVERTIME ASSESSMENT

At this point, and after a brief description of the Pombaline building construction techniques, is now important to mention the main inherent problems, not only when the reconstruction was taking place but also the current state of the buildings approximately 250 years later.

Right after the construction many were the issues to it associated. Not only due to long period of time that the rebuilding took but also as a result of modifications done to the original projects, by the landlords. Some of those problems can be highlighted, like for example the sewage system that allowed the sea to enter the sewer ducts in high tides, bringing with it the waste back to the city and consequently the nuisance odor. Furthermore, the water supply to the city, not only to the fountains but also the one to use in case of fire, was not working properly, existing many buildings without a direct supply of water. Additionally, the streets did not present the delineated layout, for many years, disregarding the safety for any person passing by once the segregation between circulation zones for pedestrians and vehicles did not exist. Regarding the architectonic aspects of every street, the desired similitude did not exist considering that the main façade of some buildings was covered with tiles, ignoring the imposed urban plan (Mascarenhas, 2004).

Despite that, over time, some of those aforementioned problems (among others) were solved at the same pace that the city was being reconstructed and the construction techniques evolved. But, even though, those modifications at the time did not carry much problems for the structural safety and integrity of the buildings, nowadays that does not apply. In the past few years and generally in the past century, in order to repair the buildings and adapt them to new needs, reconstructions were being made to the Pombaline buildings disregarding any attention for structural safety or integrity and not less important implied an identity loss in this heritage buildings.

The most common and specific modifications that did not include the reconstruction of the entire building are related to structural walls removal. This option to demolish internal structural elements that in the Pombaline timber cage are so important is directly correlated to the need of bigger areas for commercial and trade purposes. Although the esthetical and architectural benefits are considerable, it removes great part of the safety margin to overcome the stress induced to the adjacent element. Furthermore, the other structures that, in some cases, could be placed in those areas did not had the same behaviour when comparing to the original. Therefore, the connection between those elements will not be as perfect as it was before, hence, not suitable. Also, the structural wall alignment, designed to be from the foundations to the top of the building, would be breached, changing the overall building behaviour. It is also known that openings were made in the walls to new internal doors, even in the firewalls that segregated two adjacent buildings, consequently enhancing the risk of fire propagation to the contiguous building. Also regarding these partial modifications, and most commonly at the ground floor, is the loss of alignment in the main masonry façade in order to install large shop windows.

Trying to augment the building area for habitation purposes additional floors were added to the regular ones. This lead to an increase of the involved stresses, overloading the foundations and consequently reducing the structural resistance of the building. This issue was worsened by the fact that several times the new connections established to the preceding structure were not the most suitable ones once again undermining the building’s stability in case of another earthquake.

Equally important to mention are the recently made reconstructions. Although their intention is to preserve the buildings heritage for the next generations, the only preservation made is to the façade architecture. In other words, all the historic timber cage that constituted the interior structural skeleton of the building is destroyed and a new reinforced concrete or light steel framing structure take place. Thus, all the original anti-seismic structure is lost and, with it, part of the Pombaline building identity and legacy. Worthy of consideration is the interconnection between the masonry walls and the concrete that display very distinctive seismic response from each other, therefore resulting in an overall earthquake response not favourable for the integrity of the masonry.

Moreover, the Lisbon's metropolitan construction nearby these buildings altered the groundwater level which, consequently, had subjected the pine pile to wet-dry cycles for long periods of time causing them to rot.

Undoubtedly, the typical 18th century Pombaline building since their first time of existence has been submitted to non-structural and structural modifications which not only neglected the original plans for Lisbon's reconstruction, but also threatened the structural safety to them associated. Indeed, a solution for their preservation is urgent to perpetuate this historic example of anti-seismic engineering.

Structural software has been developed (S. Lagomarsino, et al., 2013) in order to study these building and an effort had also been made to retrofit those (Biscaia, et al., 2016; Lourenço, et al., 2014)

CHAPTER 6

SIMPLIFIED PUSHOVER ANALYSIS – *FRONTAL POMBALINE* WALLS

6.1 INTRODUCTION

After a description of the constructive techniques used in the typical Pombaline building, the main objective of this chapter is to study its main element, i.e. the Pombaline wall (or *frontal* wall). This type of walls are the central core of the building offering resistance to seismic events. The geometrical characteristics of the walls are myriad, mainly due to the human factor inherent to their construction. In other words, since the blueprints only existed to the façades and not the interior, all the building internal walls were adopted and erected on site according to the existing space, originating several types of walls. Even more, the walls were not all equal, as it was shown before. To simplify, in this chapter will only be presented the walls made by half lap joints, as it can be perceived in Figure 6.1.

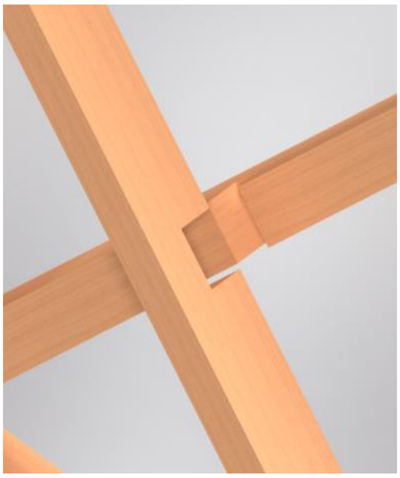


Figure 6.1 – Major *Frontal* walls connection in detail

This choice is related to the fact that previous researches were made ((Ferreira, et al., 2012; Goncalves, et al., 2015; Leonidas Kouris and Kappos, 2012, 2014; Meireles, et al., 2012)) using this sort of walls/connections, and therefore a comparison could be achieved comparing the results obtained.

The seismic pushover analysis made in this chapter is based on a single element analysis, i.e. a portion of a wall will be submitted to horizontal forces and its response will be studied.

6.2 THE *FRONTAL* BEHAVIOUR AND THE COLLAPSE MECHANISM

The response behaviour of the *frontal* walls when experiencing horizontal forces is quite ingenious and simple, presenting two correlated stages (Meireles, 2012).

The first stage is associated with low horizontal forces and reduced displacements. The masonry infill between the timber elements imputes the structure a higher stiffness, mostly as a result of the confined timber, therefore controlling the buckling phenomena of the diagonal (Gonçalves, 2015). In fact, this stage is, undoubtedly, related to the strength of the connections *prumo-travessanho* and *prumo-prumo* at the base of the wall panel. These connections are rather simple, especially the one connecting two consecutive vertical elements (*prumos*), done by a simple top to top connection. Thus, two stages can be considered that, when reached, lead to the second stage: the rotation of the wall and the rotation between *prumo* and *travessanho* at their nailed connection. This mechanisms can be observed, for example in the recent experimental results obtained by Meireles (Meireles, 2012).

When the horizontal forces reach a certain point, the infill, due to the horizontal displacement and to the poor connection to the timber, detaches from it. Therefore, the “protection” against buckling no longer exists and the timber is free to rotate as it is less constrained, now only depending on the joints and the diagonals timber elements. It is also important to mention that this stage could be seen in two perspectives. It could be mentioned that with the detachment of the masonry the stiffness would decrease, but on the other hand, the masonry weight that was attached to the structure and consequently amplifying the seismic effects no longer is present in a substantial part of the *frontal* walls. In addition, the strength of the wood is far superior when compared to the masonry.

Also imperative to mention is the importance of the diagonals in the second stage. Since there is no longer masonry infill, the diagonals in compression are the only structural elements that prevent the horizontal displacement and consequently the collapse. Likewise, the majority of this type of elements have a half lap joint at mid length in order to cross with the other diagonal. Therefore, and since the connection is not always tight and there is no masonry infill to prevent the buckling, it can be stated that the major and ultimate mechanism of collapse is the out-of-plane diagonal buckling due to the high stress concentration in that region. The previously described mechanism of collapse can be perfectly perceived in Figure 6.2.

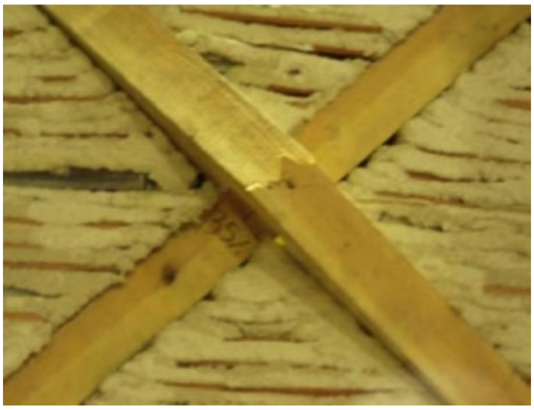



Figure 6.2 - Buckling and rupture of the diagonal - Typical collapse mechanism – Reproduced from (L. Kouris, et al., 2014)

To sum up, every Pombaline wall panel presents two major mechanisms before the collapse: the first one related to the loss of connection between the panel infill and the timber structure and the second one associated with the fact that the timber is the only structural element present. After this two “stages”, the wall no longer offers structural resistance.

6.3 STATE OF THE ART IN SEISMIC *FRONTAL* WALLS ANALYSIS

The seismic behaviour research of these major structural elements suffered an evolution, and, nowadays, it could be said that a considerable amount of knowledge has been collected.

The state of the art in seismic *frontal* walls analysis could be primarily divided into two parts: the first one regarding the experimental tests and a second one, where the knowledge acquired is applied and tested analytically, corroborating the first values obtained.

The first tests in real specimens started in 1997 with *Pompeu Santos* (Pompeu Santos, 1997) that submitted three walls taken from a Pombaline building to horizontal forces in order to obtain the first cyclic results for Pombaline walls. Hence, the first hysteretic curves were documented demonstrating that the ductility and the energy dissipation in these structures are their major strength. Two major researchs stood out: (Meireles, et al., 2012) and (Goncalves, et al., 2015). Again, three specimens where tested, although this time they were constructed and assembled in a laboratory using a similar construction technique to the first ones tested, intending to compare the two experiments. The results corroborated the ones obtained by *Pompeu Santos*. Furthermore, some simplifications were concluded: the masonry infill does not affect the response of the structure; and the initial stage of resistance depends mainly on the interconnection between the timber and the masonry infill. In addition to *Meireles et al.,* also *Ferreira et al.* in 2012 tested a wall. However, instead of building an entire wall made by multiple single modules, a single element was constructed, intending to study the single and simplest element of the structure along with the importance of the diagonal elements. Therefore, it was concluded that the importance of the compression diagonals is crucial, when compared to the tensioned ones. Again, it was observed that the masonry infill when the wall is submitted to horizontal forces, does not contribute much to the overall strength. More recently, *Gonçalves et al.* (Goncalves, et al., 2015) tested 4 walls, constructed on a laboratory, with a slight difference: two of them had masonry infill and the other two did not had. The major objective was to understand the importance and contribution of the timber frame to the overall behaviour. Also in this research three seismic retrofit solutions were tested.

It is important to notice that in all the models the construction technique was pretty similar with half-lap joints interconnecting the majority of the elements.

Even though the tests on real walls are important, the need to create models that enable the seismic study of the existing timber-framed buildings is crucial. Therefore, along with the state of the art concerning experimental tests, it is also important to mention the analytical models developed. Note that taking into consideration that these structures are quite heterogeneous and due to their non-linear behaviour, these models are only possible considering some simplifications. And for that, the experimental tests are fundamental. They make it possible to better understand the reality, and adjust the numerical models accordingly. With that in mind, *Rafaela et al.*(R. Cardoso, et al., 2005) made a seismic evaluation of the performance of a Pombaline building identifying the expected structural collapse mechanism.

In spite of the importance of the model developed to analyse the Pombaline structures, it was a time consuming analysis and quite inaccurate. Several runs had to be made and the model had to be modified after each run. However, the simplifications made (based on the experimental results) are noteworthy: the masonry infills were neglected and the diagonals were modelled with pinned connections at the end, assuming only compression loads. Despite the inadequacy of the model once it did not represent the reality, it was, at the time, the best approximation to the real behaviour of the overall building

With that in mind, and with the purpose of obtaining reliable data to use in structural evaluations, another significant research was the work done by *Ferreira et al.* (Ferreira, et al., 2012) where again the masonry infill was neglected in the numerical analysis, concluding that the diagonal members are the conditioning members to the overall behaviour and resistance. Moreover, the consideration of tensioned diagonals is negligible.

At the same time, (Meireles, et al., 2012), using the results obtained from the experimental tests, developed a hysteretic calibrated model for the timber-framed wall. This model was developed using a series of exponential and linear functions that are defined by nine different parameters. This curve was able to correctly reproduce the response of the wall under general cyclic and monotonic load. The most significant feature of this research is that the model described is currently used in a structural calculation software called *Tremuri* (A. Lagomarsino, et al., 2009).

Furthermore, (Leonidas Kouris and Kappos, 2014) developed a procedure which, using a structural program allows to model a timber-framed structure and obtain the correct response, accordingly to the input data. This means that according to the geometric and material properties of the wall, the input data in the software will vary. To obtain the procedure, the authors studied and varied the most important structural aspects, namely, the effect of the masonry and their mechanical properties.

To conclude, all the experimental results and models could not effectively reproduce the real behaviour of timber-framed walls although being very close to it. However, it is important to mention that in the great majority of the tests and models, the constructive techniques applied were the same, i.e. the type of interconnections between materials were equal. Note that if the interconnection of the diagonals are modified the response will consequently modify, and along with that, the respective response.

6.4 COMPUTATIONAL MODEL

6.4.1 INITIAL CONSIDERATIONS

The computational model adopted and used in the present document is the one developed by (Meireles, 2012). Since the results obtained by Meireles were corroborated by the experimental tests, the model was considered valid and the work here developed took her research as a starting point. Equally important is the fact that the model reproduces accurately the wall's real behaviour, using linear models that simplify the analysis.

The objective of the model is to obtain two parameters that would be used in the hysteretic model developed by *Meireles*. Those parameters were the initial stiffness and the load directly related to the collapse of the diagonal. Thus, the first model considers the wall and all the structural elements associated (with some simplifications later described), i.e. the timber and the masonry. On the other hand, the second model only uses timber as a structural element, therefore neglecting the effect of the masonry. The combination of those two linear analysis made possible for *Meireles* to obtain the values needed for her proposed hysteretic model and consequently obtaining the cyclic behaviour of the wall.

Although, in the present work the attention was directed to the first model, with the purpose of obtaining the initial stiffness and consequently the response of the wall using a new method that will be described afterwards.

In the final, the main objective is to use all the simplifications adopted in the wall model developed by *Meireles*, and consequently presenting a simpler model to reproduce the response of those when submitted to horizontal forces, by a pushover analysis.

6.4.2 DESCRIPTION OF THE MODEL

As previously mentioned, the goal is to obtain an approximate value for the initial stiffness of Pombaline walls. This prediction is based on a linear analysis, which can be considered correct since the wall displays an elastic response prior to any masonry detachment from the timber structure.

Therefore, the model considered had the following layout (Figure 6.3):

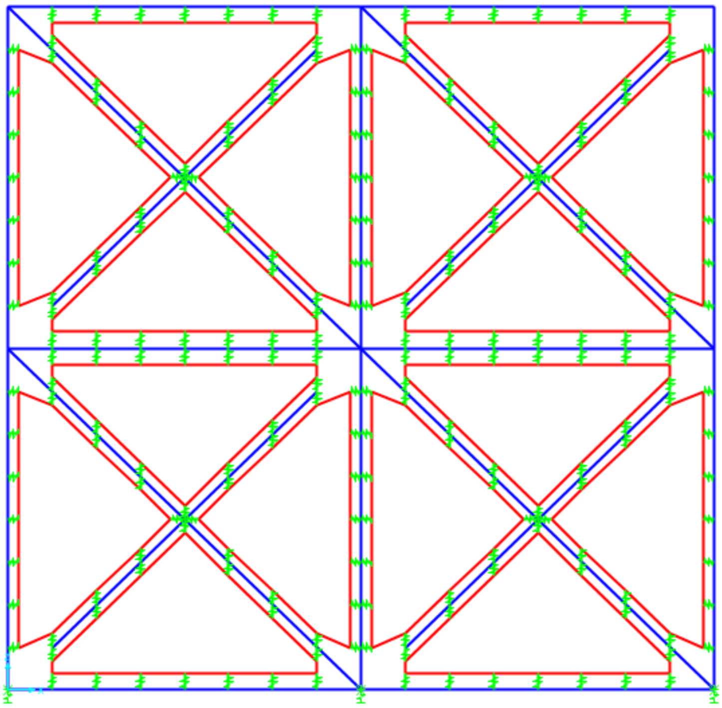


Figure 6.3 - SAP2000 model for estimating the initial stiffness

At first, the structure appears to be quite similar to the one tested on laboratory. Although, some simplifications were made, as it is usual in every analytical model, result of the previous knowledge acquired in real tests and other analytical tests. Thus, the wall was modelled using bars and shell elements with the following properties assigned:

a) All the connections between bars are pinned, except in the interconnections between diagonals, this assumption was not only applied previously by *Meireles*, but also by Kuoris (Leonidas Kouris and Kappos, 2012). As a matter of fact, this is in accordance with the type of connection used and its response when submitted to shear loads. The structure would naturally create plastic hinges at those locations;

b) The diagonals were supposed to resist only to compression loads so a limit of 0 kN was imposed for the tension forces. Taking into account the shear load imposed to the model (later described), the diagonals in one direction were also disconnected, as it can be perceived in Figure 6.4. This option is related to the type of connection involved. In other words, when the wall is subjected to a shear load applied on the top, one of the diagonal members does not contribute to an increase of the structural resistance in the overall response. Even though its structure relevance could be considered as null, it is still modelled to reproduce its self-weight;

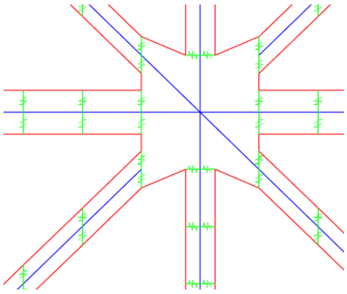


Figure 6.4 - Disconnected diagonals in the analytical model

c) Rigid links were equally distributed to connect the timber elements to the masonry. Their function is to simulate the first initial state of the connection when the wall begins to experience the horizontal forces, and the masonry is still well connected to the wood. Thus, this present model can only be used under those circumstances and, therefore, it is used to obtain the initial stiffness;

d) The masonry was modelled as a thin-shell following the Kirchhoff formulation for thin-plates neglecting transverse shear deformation;

e) To simulate the effect of rigid body linear springs were applied at the base of the vertical elements. Those were calibrated by *Meireles* with a constant stiffness of 15.000 kN/m (for compression and tension of the spring). Although in the present work that value was maintained, the spring that would be more close to reality is a bi-linear spring. In other words, when the wall rotates to one side it compresses the timber at the interconnection between vertical elements, and on the other hand, it tensions the nailed connection. Thus, those two situations do not have an equal response.

The timber sections and properties adopted to perform the present analysis (Table 6.1) were the same adopted by *Meireles*. It is important to mention that those dimensions correspond to the average dimensions commonly found in Lisbon's downtown buildings. As a matter of fact, the research done by *Mascarenhas* (Mascarenhas Mateus, 2005) corroborates that.

Table 6.1 - Pombaline walls section of the structural elements (Meireles, 2012)

Material Sections		**Width**	**Height**	**Length**	**Thickness**
Timber	Prumo	80	120	variable	n.a.
	Travessanho	120	80	variable	n.a.
	Diagonal	100	70	variable	n.a.
Masonry		n.a.	n.a.	n.a.	100
NOTE: All units mentioned are in millimetres (mm).					

Regarding the material properties assigned to the material in SAP 2000, those were described in Table 6.2, along with their references.

Table 6.2 - Pombaline walls material properties

	Young Modulus	Specific Weight	Poisson's Coefficient	Reference
	GPa	kg/m^3	-	
Timber	12	580		(*NP-4305 – Madeira serrada de pinheiro bravo para estruturas*, 1995)
			0.2	(Brazão Farinha and Correia dos Reis, 1998)
Masonry	0.77			(Carvalho, 2007)
		2242.61	0.2	(Brazão Farinha and Correia dos Reis, 1998)

The load applied to the wall is divided into two categories: vertical and horizontal. The vertical load was obtained considering a wall situated in the first floor, and the corresponding load of the top three floors situated above were supported by it. Thus, a total load of 30 kN/m was estimated and applied on top of the wall. This distribution took into account their length of influence and were concentrated on the vertical elements. The second type of load applied is horizontal. That load intends to simulate the experimental shear forces induced in the experimental pushover tests performed by several authors (Ferreira, et al., 2012; Meireles, 2012) in order to reproduce the earthquake forces acting on the *frontal* wall at the pavement level. The location of those loads is presented in the next figure (Figure 6.5).

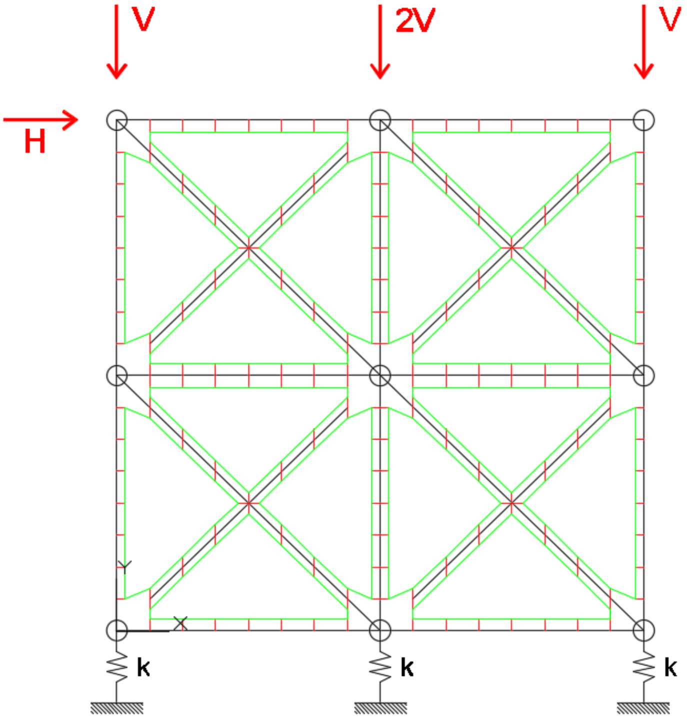


Figure 6.5 - SAP2000 load positions

6.4.3 *FRONTAL* WALL MODEL AND RESULTS

Using the software SAP2000 and following the description presented in the previous chapter regarding the materials properties and the constitutive elements, the experimental test carried out by *Meireles* was modelled in order to simulate it. Thus, the following dimensions represented on the Figure 6.6 for the symmetric wall were considered.

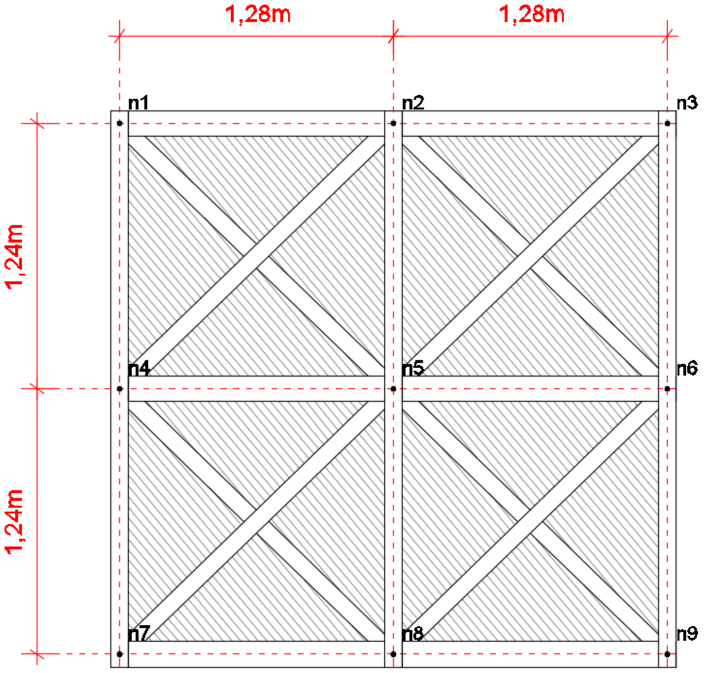


Figure 6.6 - *Frontal* 2x2 wall dimensions for the SAP2000 model

The vertical loads applied to the model intended to illustrate the dead load above the wall and supported by it, view Figure 6.7. The symmetric distribution on top of the vertical element is related to an equal weight distribution.

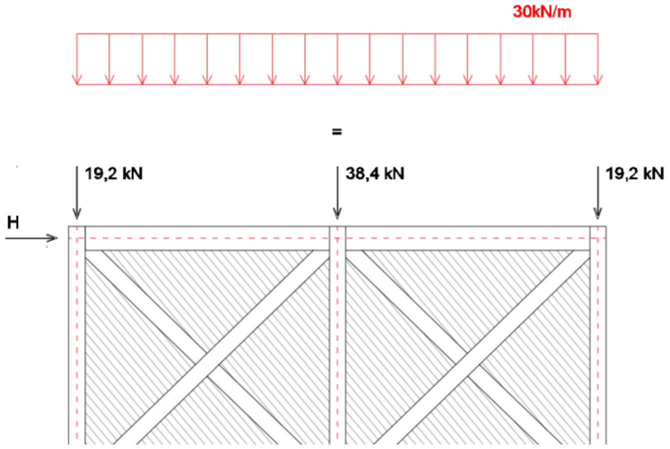


Figure 6.7 - SAP2000 load distribution

Also applied to the wall was a horizontal load. This load was modified during the analysis in order to obtain an average value for the horizontal displacement. Thus, three loads were applied for three different analysis, H=30kN, H=25kN and H=20kN. Note that the vertical load was kept constant. At this point and with the model prepared to be analysed, the objective was to obtain the horizontal displacements consequence of the loads applied. Therefore 4 runs were performed: one obtaining the vertical displacement related to the dead loads, and the other three corresponding to three different horizontal loads. The horizontal deformation could be seen in Figure 6.8.

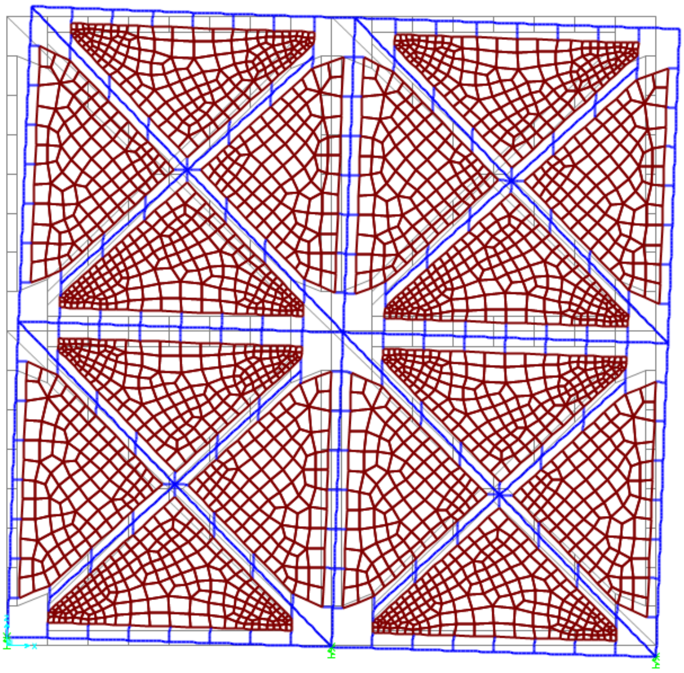


Figure 6.8 – SAP2000 wall deformation[30] when submitted to the horizontal load

Hence, the deformation results obtained are presented in Table 6.3.

Table 6.3 - SAP 2000 model horizontal displacements

Load Case	**Horizontal displacements [mm]**			
	Node	**n1**	**n2**	**n3**
Vertical (dead load)	$\delta_{H,V}$	-0.216	-0.216	-0.200
Horizontal	$\delta_{H,H=30kN}$	4.871	4.809	4.686
	$\delta_{H,H=25kN}$	4.057	4.005	3.902
	$\delta_{H,H=20kN}$	3.243	3.201	3.118

---

[30] The deformation is not scaled proportionally.

By the superposition principle, the values presented previously permitted to obtain an initial stiffness of 6,6 kN/mm. When comparing the value with the one obtained by (Meireles, 2012), the difference is almost negligible with a difference of 2.3%. One of the possible reasons for this slight difference might be the masonry mesh.

Henceforth, the model described was considered correct thus validating the proposed method to obtain the initial stiffness (k_1) of a *frontal* wall.

6.5 PROPOSED MODEL FOR THE *FRONTAL* WALL PUSHOVER ANALYSIS

Adopting the previous described model a methodology to simplify the *frontal* wall pushover analysis is in this chapter outlined. Hence, this step by step approach intended to obtain the approximate response of a wall when submitted to horizontal loads that later could be applied in an overall seismic building assessment.

The proposed methodology could be applied following the next 5 steps.

1) Acquire the geometrical data of the wall along with the mechanical properties of the structural elements, i.e. timber and masonry;
2) Model the linear elastic structure according to the model described in chapter 6.4;
3) Obtain the initial stiffness, k_1;
4) Consider the stiffness of the second stage, k_2 equal to $1.5\%\ k_1$;
5) Use the following $F - \delta$ curve (adapted from [45]), which is proposed to simulate the structural behaviour of the *frontal*, assuming that the monotonic test curve is similar to the envelope curve of the cyclic tests:

$$H = \frac{(k_1 - k_2)\delta}{\left[1 + \left(\frac{(k_1 - k_2)\delta}{0.9f_0}\right)^{1.5}\right]^{\frac{1}{1.5}}} + k_2\delta \tag{6.1}$$

Where:

$-$ k_1 is the initial stiffness;

$-$ k_2 is the second stage stiffness;

$-$ δ is the top horizontal displacement of the wall;

$-$ f_0 is the diagonal’s axial collapse force;

$-$ F is the top horizontal force applied to the wall.

Also important to mention is that the previously described method could only be applied to walls with half lap joints interconnecting the diagonals. For other connection types the present methodology have to be verified, based on experimental results.

In order to corroborate the described methodology, the same was applied using the results obtained from the chapter 6.4.3 and consequently comparing it with the available experimental results. Therefore, the $F - \delta$ characteristic curve of the wall was drawn and compared with the results obtained from the specimen SC2 (Meireles, 2012) (Figure 6.9) and specimen SC3 (Figure 6.10). The values used in the expression 6.1 were:

- 6,7 kN/mm for the initial stiffness (k_1) obtained from the SAP2000 model;
- 0,1005 kN/mm for k_2;
- 49,09 kN for f_0 (this value is described by *Meireles* as the axial collapse load).

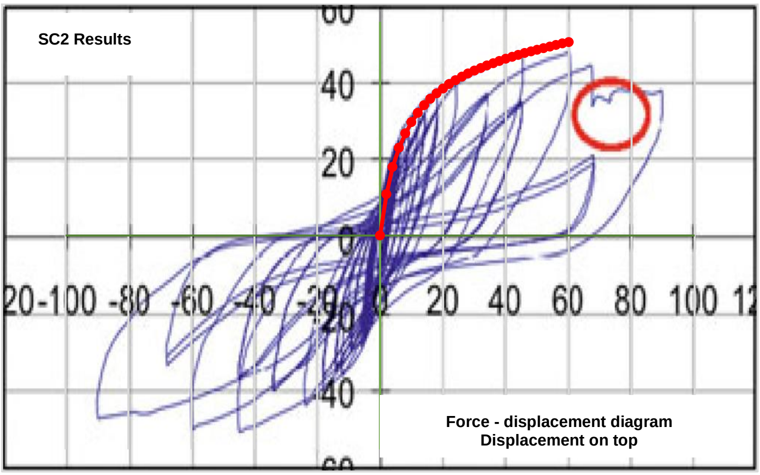


Figure 6.9 – Comparison between *Meireles* SC2 experimental results and the suggested methodology

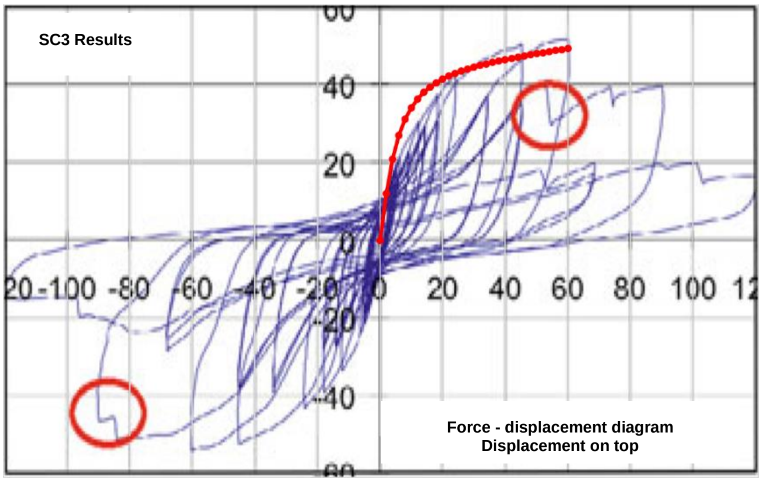


Figure 6.10 - Comparison between Meireles SC3 experimental results and the suggested methodology

Comparing the $F - \delta$ curve with the experimental envelope of specimen SC2 and SC3 there is a reasonable good match, as it can be seen previously. In the same way, and with the purpose of corroborating the application of the presented methodology to other walls, the results attained by *Pompeu* (Pompeu Santos, 1997) were also tested. Although and since the material properties were not all available, the linear model to find out the initial stiffness may not conduct to trustworthy results. Therefore, a value extrapolated from the initial stiffness of the tests was obtained. The initial stiffness calculated for the G1 specimen (Pompeu Santos, 1997) was 7.9 kN/mm. Despite the fact that the previously mentioned value was not obtained using the initial

SAP2000 model, preconized in the methodology suggested, the value can be applied in the formulation in the same way. Also important to mention is that the f_0 force now considered was the same as the one obtained by *Meireles* (49,09 kN). This assumption was made due to the fact that the cross-section geometry of *Pompeu's* specimens is quite similar to the ones tested by *Meireles*. Furthermore, the diagonal connection type was the same in both tested specimens. The main differences between the tests are the number of frames (2x2 in (Meireles, 2012) and 3x2 in (Pompeu Santos, 1997)) and the vertical load applied to the *frontal* (null in (Pompeu Santos, 1997)).

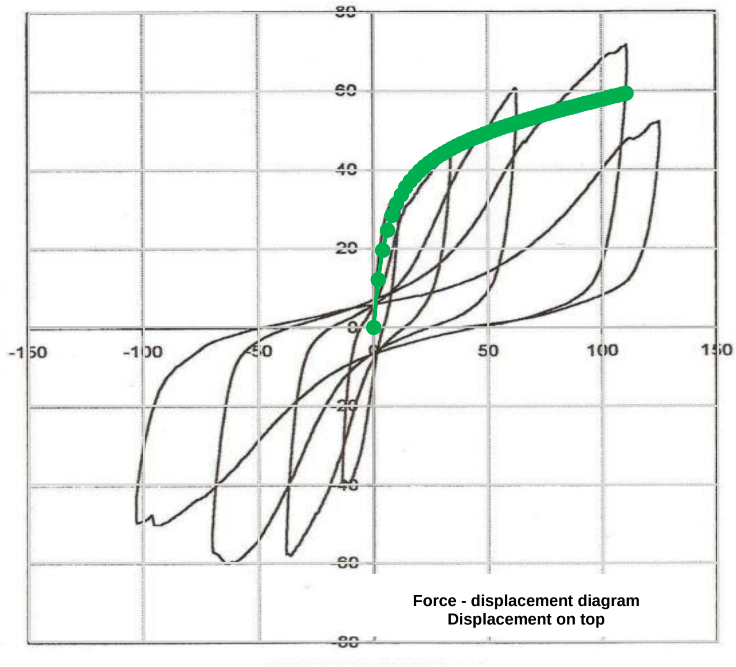


Figure 6.11 - Comparison between Pompeu G1 (Pompeu Santos, 1997) experimental results and the methodology suggested

Despite the extrapolation of values and the differences between both tests, there is a reasonable match between the experimental results and the $F - \delta$ curve, as it can be seen in Figure 6.11.

The main objective of the bi-linear model is to estimate the overall response achieved, in order to implement it in a complete model of the building.

Hence, and with that in mind, a slightly different model from the one described in the chapter 6.4.2 is presented although with some changes in the structural element connections. Again, the software used to model was the SAP2000. It is important to mention that the main feature of the model now described is that it only has two types of elements to simulate the global response of the wall. The model is presented in Figure 6.12 and is characterized by:

a) Vertical elements (*prumos)* simply supported at the bottom;
b) Vertical elements modelled continuous from top to bottom;

c) The horizontal elements (*travessanhos*) were modelled connecting two consecutive vertical elements;

d) The diagonals were not modelled. Instead of it, nonlinear links were implemented as it can be seen in Figure 6.12.

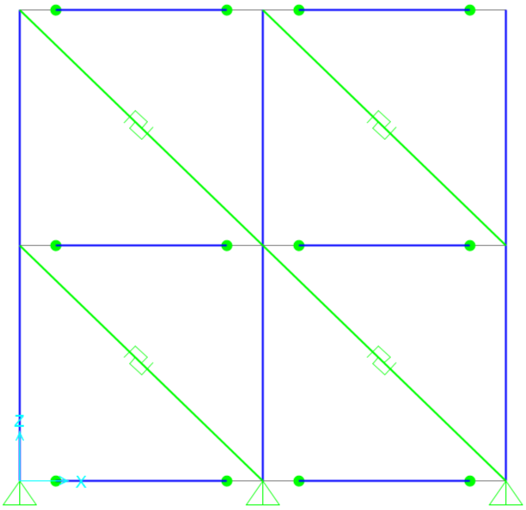


Figure 6.12 - SAP2000 model for pushover analysis

For the force-displacement properties of the diagonal link (green lines in Figure 6.12), the following expression is proposed, based on the calibration of the experimental tests:

$$F = \frac{(k_1 + 0.2k_2)\delta}{\left[1 + \left(\frac{(k_1 - 0.2k_2)\delta}{0.36 f_0}\right)^3\right]^{\frac{1}{3}}} - 0.2\,k_2\delta\,, \qquad \delta \in [-0.04; 0.04] \tag{6.2}$$

When the curve reaches the stage corresponding to a value of $\delta = 0{,}04 \vee \delta = -0{,}04$ it shall be considered that it descends linearly towards 0, in order to represent the strength degradation after collapsing.

Therefore, and considering the values previously obtained, the curve that characterizes the link is illustrated in Figure 6.13.

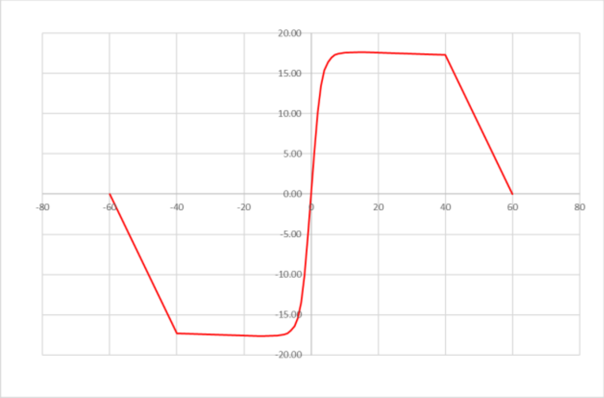


Figure 6.13 – Link's force-displacement behaviour proposed to simulate the *Meireles* SC2 specimen

After the input of the previous data, the model was submitted to a pushover analysis resulting the displacement seen in Figure 6.14 and the pushover curve seen in Figure 6.15.

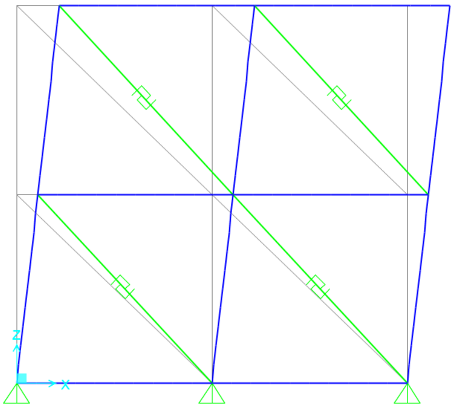
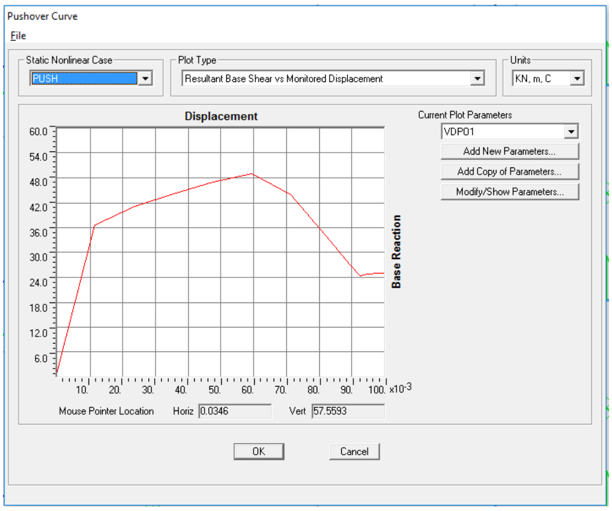


Figure 6.14 - Deformation of the SAP2000 model when submitted to a pushover analysis


Pushover Curve

Static Nonlinear Case: PUSH

Plot Type: Resultant Base Shear vs Monitored Displacement

Units: KN, m, C

Current Plot Parameters: VDP01

Mouse Pointer Location Horiz 0.0346 Vert 57.5593

Figure 6.15 - Pushover curve obtained using the SAP2000 with nonlinear links

When comparing the results obtained with this model, they were quite similar to the ones experimentally obtained by Meireles, as it can be seen in Figure 6.16 and Figure 6.17, where the envelope was compared with the pushover curve represented in Figure 6.15. Although some improvements could be done to the model that right now could be considered in a developing phase. Those developments will focus on the rocking movement simulation that in the present model is not simulated, but in an overall building analysis could conduct to differences in results.

However, it can be concluded that they represent a good approach and a suitable methodology to be applied to other walls and/or studies.

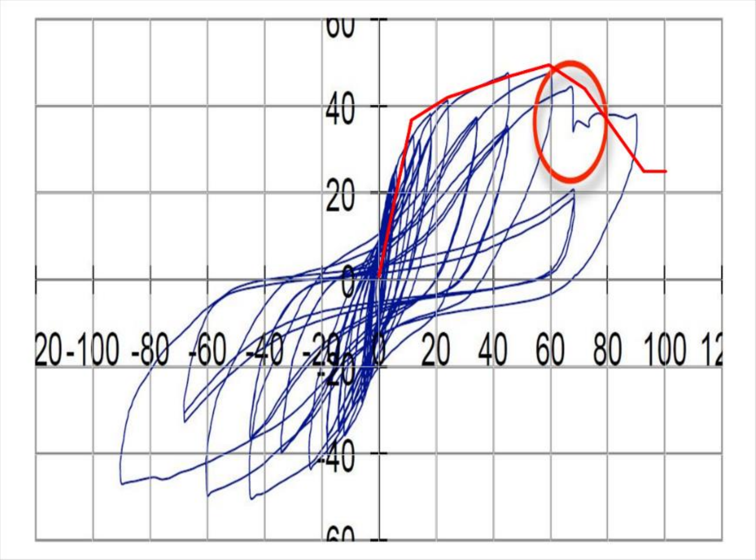


Figure 6.16 - Results comparison between the new methodology proposed and SC2 specimen results

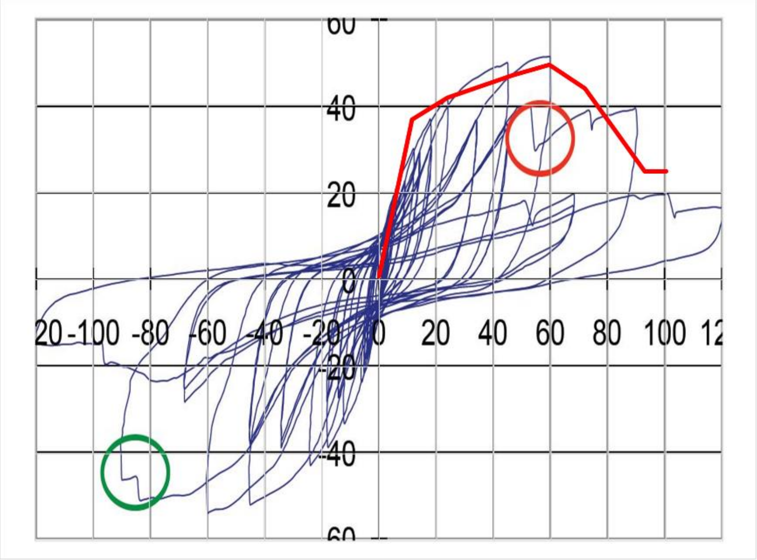


Figure 6.17 - Results comparasion between the new methodology proposed and SC3 specimen results

Generally speaking, the described model could be considered reliable and valid for the Meireles specimens presenting a reasonably good match to the experimental envelopes. Therefore, assuming that the monotonic test curve is similar to the envelope curve of the cyclic tests, the behaviour of the *frontal* walls can be done without much computational effort by reproducing the masonry effect and the strength of the compressed diagonal using a nonlinear link. Having this basic element of the *frontal* wall calibrated, it is possible to replicate its behaviour for all the *frontal* walls, simplifying in this way the global model of the Pombaline building.

CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

7.1 CONCLUSIONS

The present work was divided mainly in three parts: a first one where a historical overview was made; a second one related to the understanding of the constructive techniques applied during the construction of the Pombaline buildings and finally a third one focused on the *frontal* walls structural analysis.

The first part intended to present a contextualization of Lisbon before and after the earthquake. A detailed perception of how the city was arranged was crucial to better understand the urgent need of a new urban project. Coupled with the city's reconstruction plans and correct urban planning were the laws implemented by *Marquês de Pombal*. They were a milestone in Portugal's history (and probably in the world) since the civil protective measures applied in the building reconstruction had a remarkable effect in the constructions that came afterwards. Those were required and mandatory in every building, otherwise the building would be demolished and the reconstruction would start over. Generally speaking, this first part made possible to understand not only the changes needed but also the innovative measures applied regarding civil protection.

The second part consisted on a characterization of the typical constructive techniques applied in the Pombaline buildings. This was crucial to perform a better analysis to the respective buildings in the present work. Hence, the correct interpretation and awareness of the mechanics involved are decisive in every structural analysis and it can be considered as the most important factor. Certainly, the perception of how a structure will respond when submitted to a certain load is fundamental therefore, the research executed analysing the assembly types used in the *Gaiola Pombalina*, represented a huge contribute for this study. By the same way, it was found that there are several types of connections and which one could conduct to different results. The present work (and others previously done) adopted the half-lap joint as the common connection between elements, namely in the diagonals. Although, if we would consider a diagonal split in half at the interconnection, that would conduct to a different behaviour depending on the force direction and consequently needed a similar methodology to be modelled. Equally, all connections were considered tight, i.e. there were no gaps in the connections, which do not correspond to the reality. Therefore, the field research done provided a better perception of the problem. The timber assembly involved in the construction of this type of buildings was, almost always, a non-tight fit and quite rudimental. Identically, the iron nails used to connect all the parts represent an important piece so far neglected in other analytical researches, or assumed as having a null effect. All things considered, this type of buildings can be considered particularly heterogeneous and difficult to analyse, taking into account that small changes in the interconnection may lead to differences in the seismic behaviour.

The third and last part of the present document intended to present a methodology for the structural analysis of *frontal* walls, i.e. the key-piece response to a seismic event. Firstly, the explanation of how the structure collapses made it possible to understand that a bi-linear model could perfectly be considered to simulate the overall behaviour of the wall. In addition, the fact that the masonry could be neglected in the second stage simplified the analytical models. The combination of this aspects permitted the proposition of two different models. The first model suggested, takes the SAP2000 model proposed by Meireles as a starting point, and using only two parameters (the initial stiffness and the axial collapse load) proposes a force-displacement curve model that reproduces very well the structural behaviour of a basic *frontal* wall. Although it was compared to other experimental results, the presented methodology should be tested to other wall configurations and compared with some new laboratory experiences. For example, the study of how the axial collapse load influences the wall response should be deeply analysed, since that could represent an efficient manner to retrofit those structural elements. Also important to mention is that the methodology is quite simple to be applied and the input data needed is obtained without effort. Later, a second model was proposed which using the results of the first one, namely the formulation, permitted to simplify even more this seismic analysis. This solution, due to its simplicity, allows to model an entire building composed of this walls and therefore, to obtain its global response.

Although not yet exhaustively tested, the model achieved, lead the way to the research of a new model that could easily simulate the wall in a pushover analysis. That was the primary objective of the present dissertation, since the seismic assessment of Pombaline buildings is considered today rather difficult and time-consuming. Therefore, the objective of simplifying the respective analysis creating equivalent structures that all assembled simulate the global building’s response is an accomplishment.

Hence, the model proposed is quite straightforward and with only bars and diagonal links the wall response was replicated with a reasonable good match for the *Meireles* results, thus concluding that the use of this new described methodology could be applied. However, the continuation of the investigative work shall be made in order to broaden its applicability. Namely, the implementation of variables that take into account the several possible wall configurations along with the test of other connection types and their influence in the diagonal links used are only two of the numerous possibilities.

All things considered and despite the transversal approach of this present work, the effort to understand the origin of this structures and how they work were the driving force for this achievement, expecting that the herein described methodology could soon help to preserve these historical buildings.

7.2 FUTURE DEVELOPMENTS

The present work raised many problems and difficulties mainly due to the lack of sufficient experimental data information to perform a better analysis. Although, it is important to realise that the problems found are part of the research process leading towards the final solution. Hence, the below presented suggestions for further developments can be considered:

a) Since it was found that the diagonals represented the key-piece of the *frontal* wall's response, the analysis of its resistance and rupture conditions are crucial to integrate those results in an improved wall model. This would be of the utmost relevance if the the study associated the type of diagonals tested to their influence in overall wall behaviour, along with the prediction of their collapse load;
b) Also regarding the walls, the interconnection research between elements and their implication in the structural behaviour of the *Gaiola Pombalina* could lead to interesting results predicting new types of collapse mechanisms;
c) The study of structural retrofitting systems for this structures, with the main objective to preserve them for the future without neglecting the most recent structural seismic building codes, would also be important;
d) Analyse of the influence of the wood floor pavements transferring the horizontal loads and the importance of obtaining a rigid diaphragm behaviour;
e) Perceive the influence of the external masonry wall coupled with the external timber structure.

BIBLIOGRAPHY

Aguirre, B. E. (2012). Better Disaster Statistics: The Lisbon Earthquake. *Journal of Interdisciplinary History*, *43*(1), 27–42.

Appleton, J. (2011). *Reabilitação de Edifícios Antigos: Patologias e Tecnologias de Intervenção*. (ORION, Ed.) (2nd Edition).

Augusto Leitão, L. (1896). *Arma de Engenharia - Curso Elementar de Construcções*. (I. Nacional, Ed.).

Barreiros, M. H. (2008). Urban Landscapes: Houses, Streets and Squares of 18th Century Lisbon. *Journal of Early Modern History*, *12*(3/4), 205–232.

Biscaia, H., Franco, N., Chastre, C., and Nunes, R. (2016). Old suspended timber floors flexurally-strengthened with different structural materials. *Key Engineering Materials*, *713*, 78–81.

Bozzano, P. M. F. (2011). Revisiting the February 6th 1783 Scilla (Calabria , Italy) landslide and tsunami by numerical simulation, 273–286.

Branca, S., Azzaro, R., De Beni, E., Chester, D., and Duncan, A. (2015). Impacts of the 1669 eruption and the 1693 earthquakes on the Etna Region (Eastern Sicily, Italy): An example of recovery and response of a small area to extreme events.

Brazão Farinha, J., and Correia dos Reis, A. (1998). *Tabelas Técnicas*. Edições Técnicas E.T.L. Lda.

Cardoso, M. R. P. (2002). *Vulnerabilidade Sísmica de Estruturas Antigas de Alvenaria - Aplicação a um Edifício Pombalino*. Instituto Superior Técnico.

Cardoso, R., Lopes, M., and Bento, R. (2005). Seismic evaluation of old masonry buildings. Part I: Method description and application to a case-study. *Engineering Structures*, *27*(14), 2024–2035.

Carvalho, J. (2007). *Caracterização mecânica de paredes resistentes em alvenaria de pedra através de ensaios não destrutivos*. Instituto Superior Técnico.

Chester, D. K. (2001). The 1755 Lisbon earthquake. *Progress in Physical Geography*, *25*(3), 363–383.

Dipasquale, L., Sidik, D. O., and Mecca, S. (2015). Local seismic culture and earthquake-resistant devices: Case study of Casa Baraccata. In V. Mileto, C and Vegas, F and GarciaSoriano, L and Cristini (Ed.) (pp. 255–260). 6000 BROKEN SOUND PARKWAY NW, STE 300, BOCA RATON, FL 33487-2742 USA: Crc Press-Taylor & Francis Group. Retrieved from

FEMA 313 - Promoting the Adoption and Enforcement of Seismic Building Codes: A Guidebook for State Earthquake and Mitigation Managers. (1998). Washington D.C.: Department of Urban and Regional Planning, University of Illinois at Urbana-Champaign.

Ferreira, J. G., Teixeira, M. J., Duţu, A., Branco, F. A., and Gonçalves, A. M. (2012). Experimental Evaluation and Numerical Modelling of Timber-Framed Walls. *Experimental Techniques*, *38*(4), 45–53.

FLAD. (2005). *O Grande Terramoto de Lisboa: providências do Marquês de Pombal*.

França, J.-A. (1989). *A Reconstrução de Lisboa e a Arquitectura Pombalina*.

Galassi, S., Ruggieri, N., and Calabria, U. (2014). Stability and Stiffness Contribution of the masonry in the Borbone Anti-seismic System. In *9th International Masonry Conference, Guimarães 2014* (p. 9).

Gonçalves, A. (2015). *Reabilitação estrutural de paredes de frontal em edifícios Pombalinos*. Instuto Superior Técnico.

Goncalves, A. M., Ferreira, J. G., Guerreiro, L., and Branco, F. (2015). Experimental characterization of timber framed masonry walls cyclic behaviour. *Structural Engineering and Mechanics*, *53*(2), 189–204

Kouris, L., and Kappos, A. (2012). Detailed and simplified non-linear models for timber-framed masonry structures. *Journal of Cultural Heritage*, *13*(1), 47–58.

Kouris, L., and Kappos, A. (2014). A practice-oriented model for pushover analysis of a class of timber-framed masonry buildings. *Engineering Structures*, *75*, 489–506.

Kouris, L., Meireles, H., Bento, R., and Kappos, A. J. (2014). Simple and complex modelling of timber-framed masonry walls in Pombalino buildings. *Bulletin of Earthquake Engineering*, *12*(4), 1777–1803.

Lagomarsino, A., Galasco, A., Penna, A., and Cattari, S. (2009). TREMURI program: Seismic analyses of 3D masonry buildings. University of Genoa.

Lagomarsino, S., Penna, A., Galasco, A., and Cattari, S. (2013). TREMURI program: An equivalent frame model for the nonlinear seismic analysis of masonry buildings. *Engineering Structures*, *56*, 1787–1799.

Langenbach, R. (2007). From “Opus Craticium” to the “Chicago Frame”: Earthquake-Resistant Traditional Construction

Ligresti, D., and Grasso, S. (2009). Historical view of the damage caused by the 1693 Catania earthquake and the reconstruction activities. *WIT Transactions on the Built Environment*, *110*, 323–331

Lourenço, P. B., Vasconcelos, G., and Poletti, E. (2014). Edifícios Pombalinos : Comportamento e reforço. In *Seminário Intervir em construções existentes de madeira* (pp. 103–112).

Mascarenhas, J. (2004). *Sistemas de Construção V - O Edifício de Rendimento da Baixa Pombalina de Lisboa. Materiais Básicos (3.ª Parte): o vidro*. Livros Horizonte.

Mascarenhas Mateus, J. (2005). *Reabilitação Urbana - Baixa Pombalina: bases para uma intervenção de salvaguarda* (Câmara Mun).

Meireles, H. (2012). *Seismic Vulnerability of Pombalino Buildings*. Instituto Superior Técnico.

Meireles, H., Bento, R., Cattari, S., and Lagomarsino, S. (2012). A hysteretic model for “frontal” walls in Pombalino buildings. *Bulletin of Earthquake Engineering*, *10*(5), 1481–1502.

Mendes-Victor, L. A., Oliveira, C. S., Azevedo, J., and Ribeiro, A. (2009). *The 1755 Lisbon Earthquake : Revisited*. Springer Netherlands.

NP-4305 – Madeira serrada de pinheiro bravo para estruturas. (1995).

Oliveira, C. S. (2008). Lisbon earthquake scenarios: A review on uncertainties, from earthquake source to vulnerability modelling. *Soil Dynamics and Earthquake Engineering*, *28*(10–11), 890–913.

Oliveira, V., and Pinho, P. (2010). Lisbon. *Cities*, *27*(5), 405–419.

Pinho, F. F. S. (2008). *Paredes de Edifícios Antigos em Portugal* (2nd Editio). Lisboa: LNEC.

Pompeu Santos, S. (1997). Ensaios de Paredes Pombalinas. *Techincal Report N.º15/97, NCE/DE, LNEC*.

Ramos, L., and Lourenço, P. B. (2000). Análise das Técnicas de Construção Pombalina e Apreciação do Estado de Conservação Estrutural do Quarteirão do Martinho da Arcada. *Revista Engenharia Civil*, (7), 35–46.

Ratton, J. (1813). *Recordações de Jacome Ratton sobre as occurrencias do seu tempo em Portugal, durante o lapso de sesenta e tres annos e meio, alias de Maio 1747 a Setembro de 1810*. Londres: H. Bryer, Bridge-Street, Blackfriars.

SAP 2000 - Integrated Software for Structural Analysis & Design. (1998). Berkeley, California, USA: CSI - Computers and Structures, Inc.

Scawthorn, C., and Chen, W.-F. (2002). *Earthquake Engineering Handbook*. CRC PRESS-TAYLOR & FRANCIS GROUP.

Tobriner, S. (1980). Earthquakes and Planning in the 17th and 18th Centuries. *Journal of Architectural Education*, *33*(4), 11–15.

Tobriner, S. (1982). *The genesis of Noto : an eighteenth-century Sicilian city*. University of California Press.

Tobriner, S. (1983). La Casa Baraccata: Earthquake-Resistant Construction in 18th-Century Calabria. *Journal of the Society of Architectural Historians*, *42*(2), 131–138.

Tobriner, S. (1999). Wooden Architecture and Earthquakes in Turkey : A Reconnaissance Report and Commentary on the performance of wooden structures in the Turkish earthquakes of 17 August and 12 November 1999 1. *Earthquake-Safe: Lessons To Be Learned From Traditional Construction, Paris, France*, (November), 1–12.

Vieux-Champagne, F., Sieffert, Y., Grange, S., Polastri, A., Ceccotti, A., and Daudeville, L. (2014). Experimental analysis of seismic resistance of timber-framed structures with stones and earth infill.

Vivenzio, G. (1783). *Istoria e teoria de'tremuoti in generale ed in particolare di quelli della Calabria, e di Messina del MDCCLXXXIII*.

Zack, M. (2015). Rebuilding Mathematically: A Study of the Rebuilding of Lisbon and London.